

**USQCD BSM**

**BNL workshop 2012**

# **The Composite Higgs Mechanism and the Conformal Window**

**Lattice Higgs Collaboration (LHC)**

**with Zoltan Fodor, Kieran Holland, Daniel Negradi,  
Chris Schroeder, Chik Him Wong**

**Julius Kuti**

**University of California, San Diego**

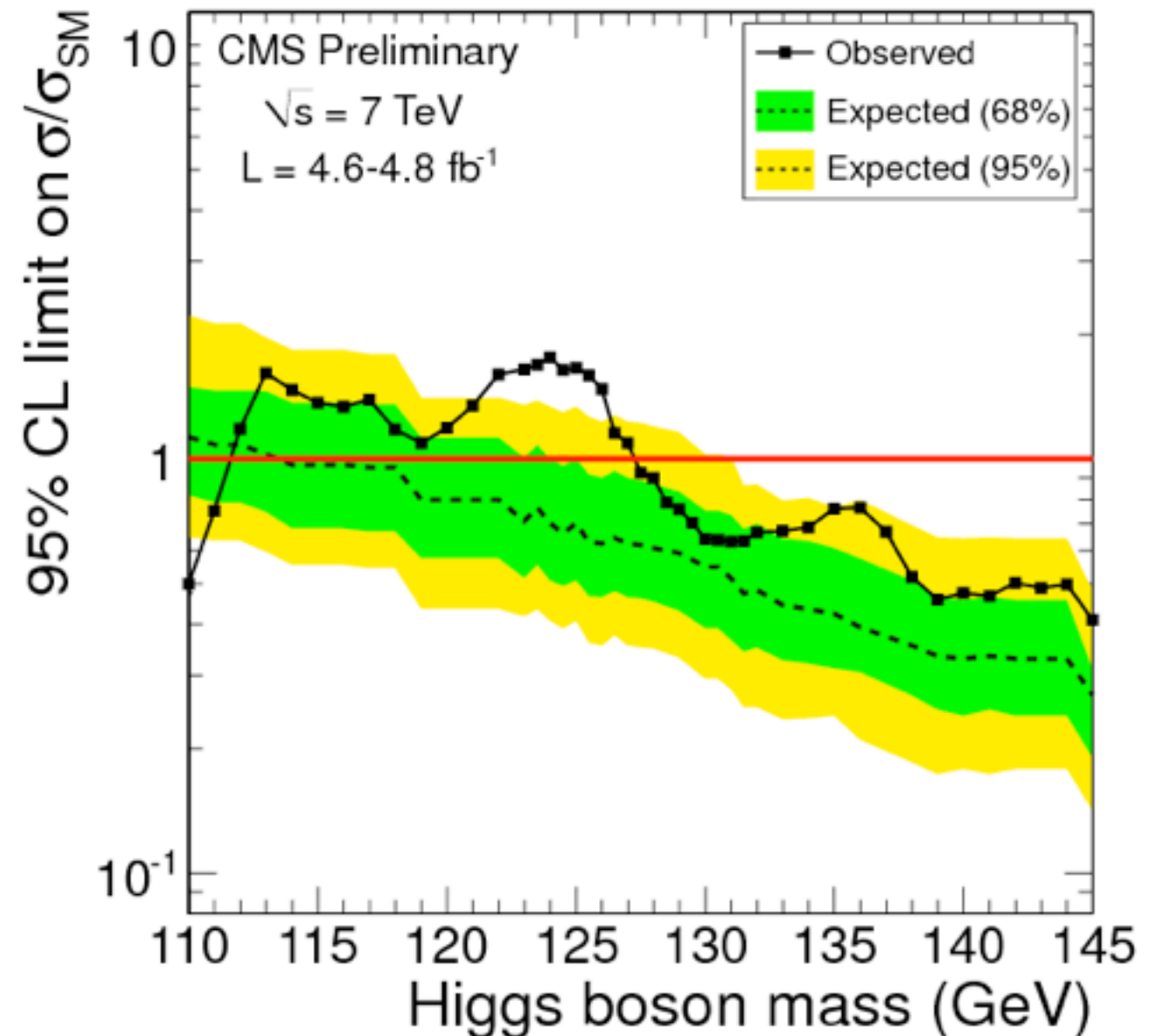
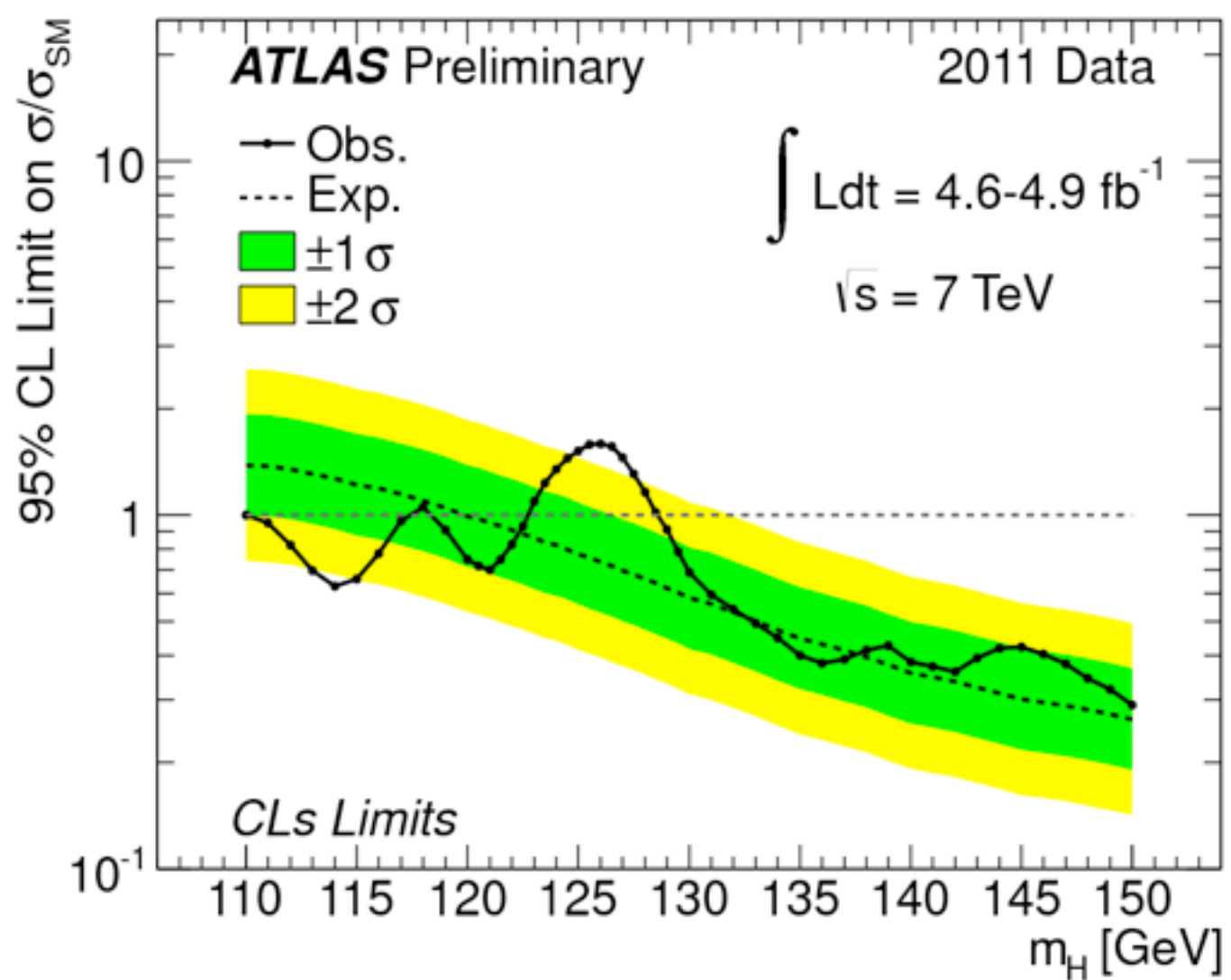
**New Horizons for Lattice Computations with Chiral Fermions  
BNL May 14, 2012**

# Outline

- **LHC Higgs search and BSM implications**  
focus on  $SU(3)$  fermion representation with two flavors
- **Two RG based strategies**
- **New results on the  $N_f=2$  sextet model in the  $SU(3)$  color rep**
- **Cosmology connection**  
(dark baryon matter and EW phase transition)
- **Conformal FSS method**
- **New results on FSS in the  $N_f=12$  model in the fundamental  $SU(3)$  rep**
- **Outlook**

# Atlas and CMS compared (from Vivek Sharma)

For low Higgs mass hypothesis both CMS & ATLAS see an excess in event yield over expected background



ATLAS excess at  $M \approx 126 \text{ GeV}$

CMS excess at  $M \approx 125 \text{ GeV}$

## **What comes at the end of the LHC run?**

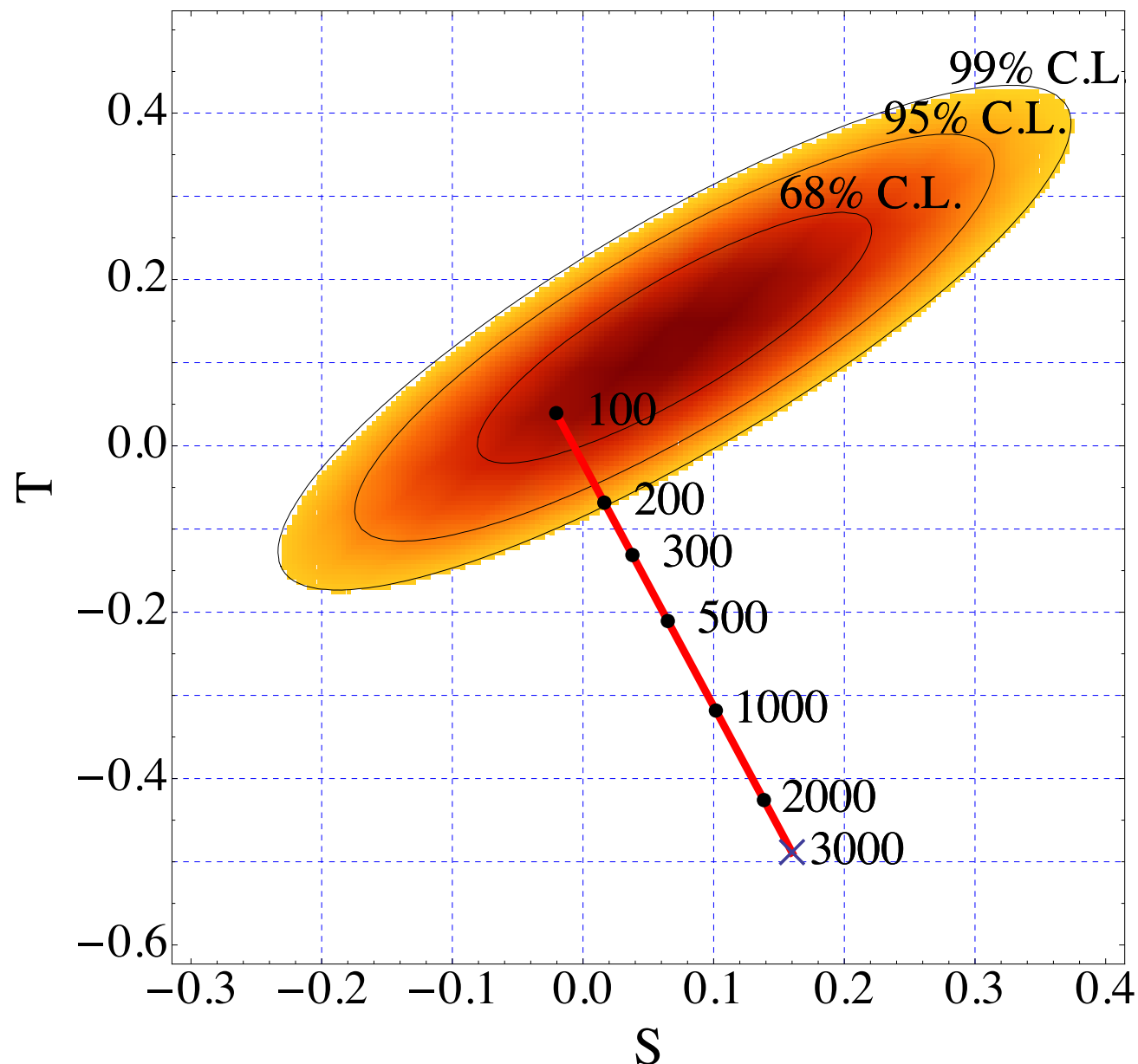
- light Higgs with non-SM couplings (dilaton?)
- Heavy Higgs, or Higgsless
- SM Higgs (SUSY symmetry breaking?)
- **USQCD composite Higgs and SUSY - timely efforts**

## What comes at the end of the LHC run?

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- USQCD composite Higgs and SUSY - timely efforts
  - Composite Higgs mechanism
  - The paradigm is important again
  - Higgsless QCD-like (cutoff  $\Lambda$  to 3 TeV)
  - changes close to conformal window
  - non-perturbative lattice studies needed
  - USQCD effort:

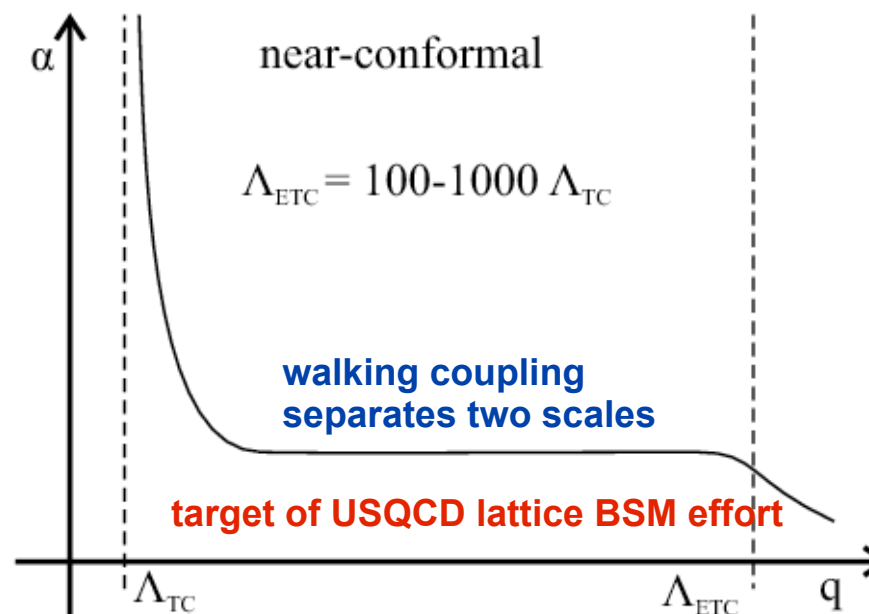
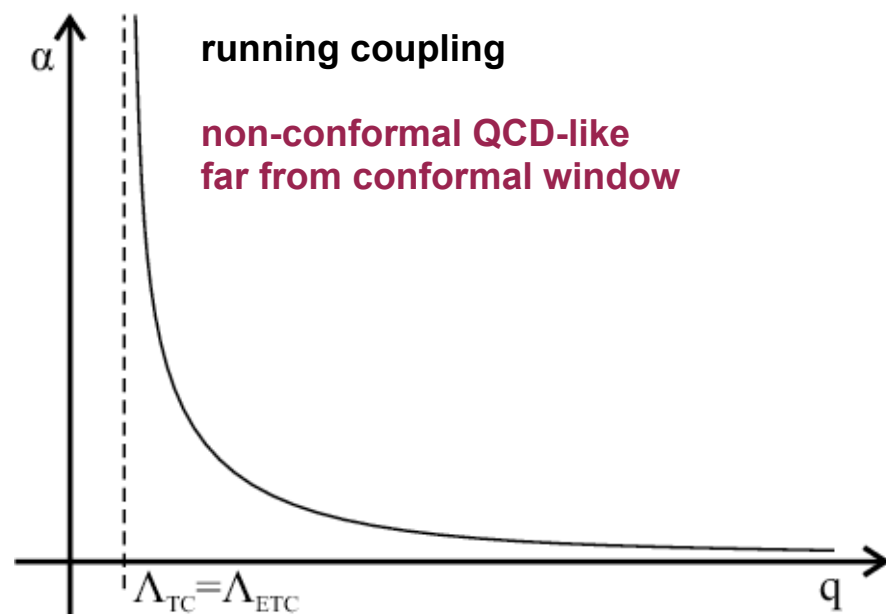
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- Composite Higgs mechanism
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- USQCD effort:

$$S = 4\pi N_D \lim_{Q^2 \rightarrow 0} \frac{d}{dQ^2} \Pi_{V-A}(Q^2) - \Delta S_{SM}$$



original Technicolor paradigm  
replaced with sextet  $SU(3)$  color rep:

- one massless fermion doublet  
chiral SB

$$\begin{bmatrix} u \\ d \end{bmatrix}$$

- three Goldstone pions

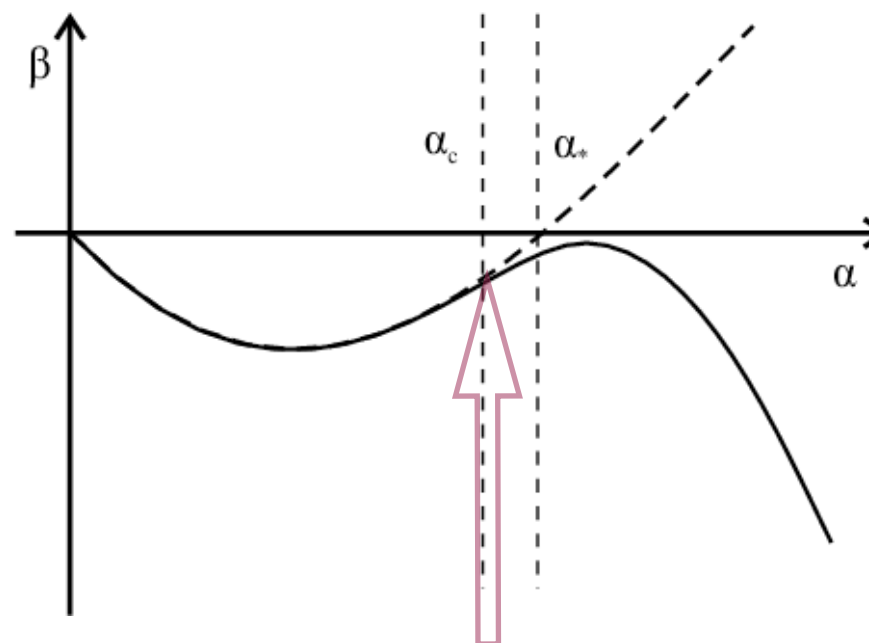
- become longitudinal  
components of weak bosons

$$\Lambda_{TC} \sim TeV$$

- composite Higgs mechanism  
scale of Higgs condensate  $\sim F=250$  GeV

- flavor changing currents and fermion  
mass generation would be problems

- conflicts with EW precision constraints?



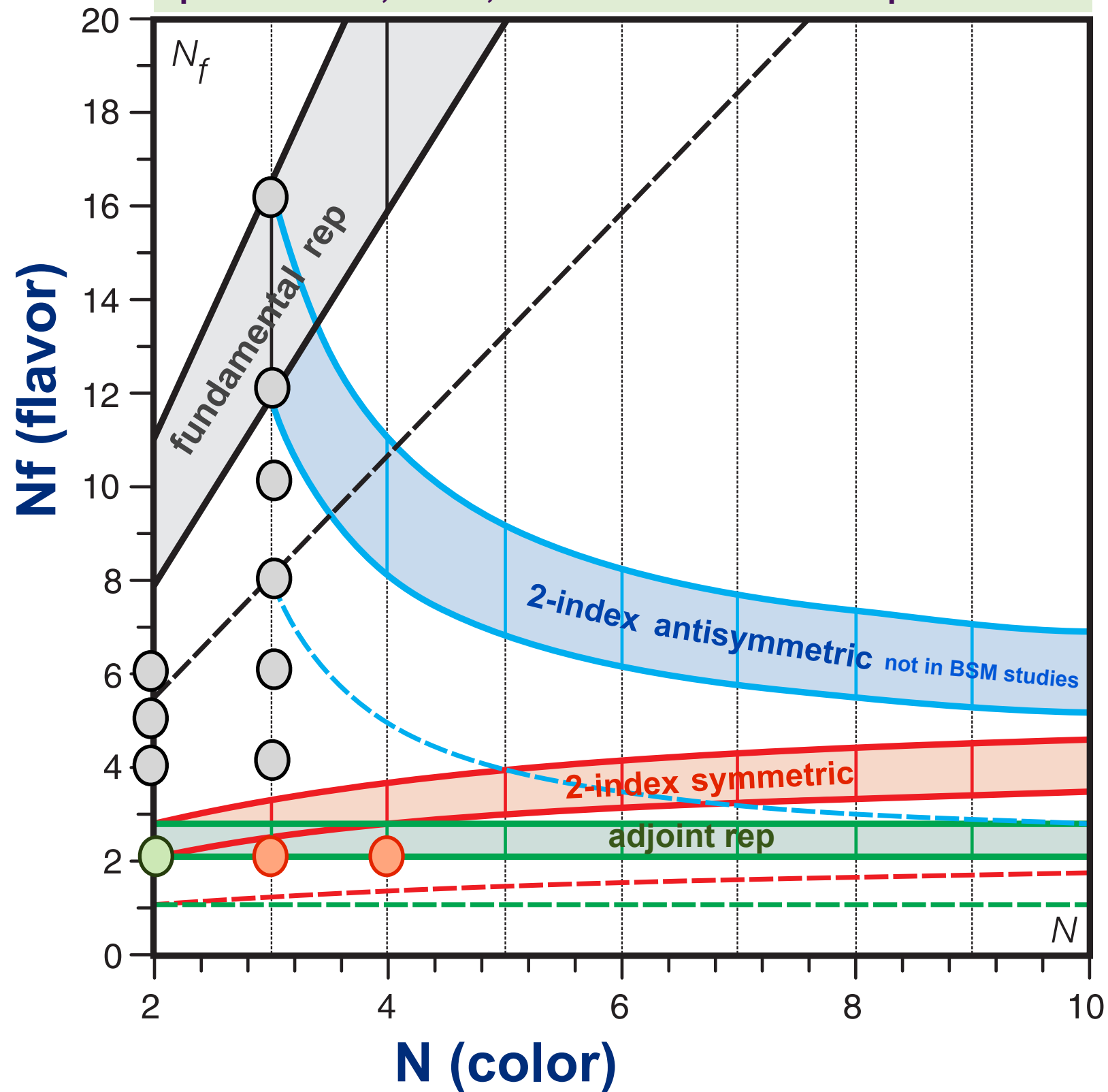
Chiral symmetry breaking turns  
conformal FP into walking

Extended Technicolor paradigm:

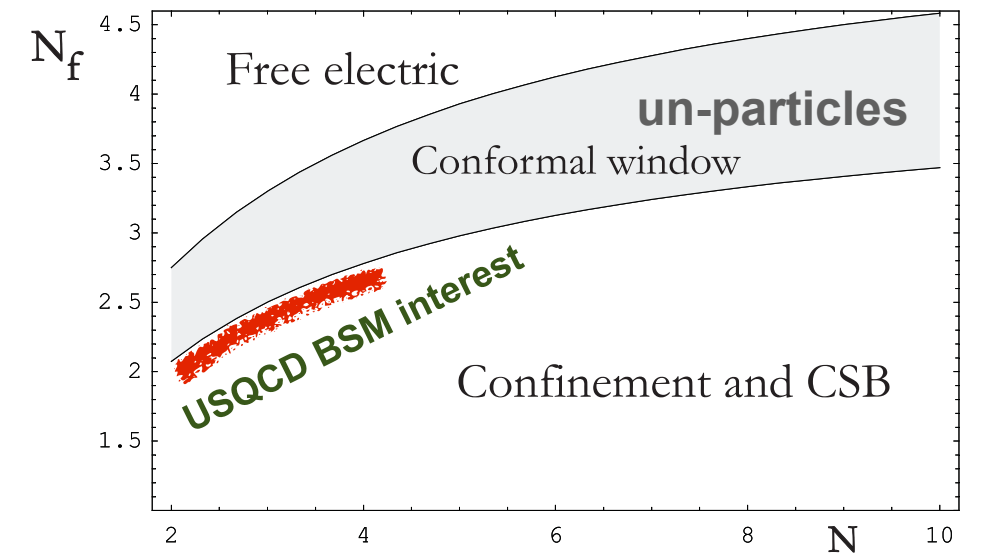
- requires walking gauge coupling  
chiral SB on  $\Lambda_{TC} \sim TeV$  scale
- fermion mass generation from  
scale at  $\Lambda_{ETC} \sim 100 - 1000 \Lambda_{TC}$
- can solve problem of flavor changing  
currents
- composite Higgs mechanism
- broken scale invariance (Dilaton)  $\rightarrow$   
light non-SM composite Higgs  
particle?
- can avoid conflict with EW precision  
constraints
- candidate models require non-  
perturbative lattice studies
- focus is on composite Higgs  
mechanism

important for lattice studies in BSM theory space

**theory space and conformal window**  
**critically important for composite Higgs**  
 space of color, flavor, and massless fermion representation



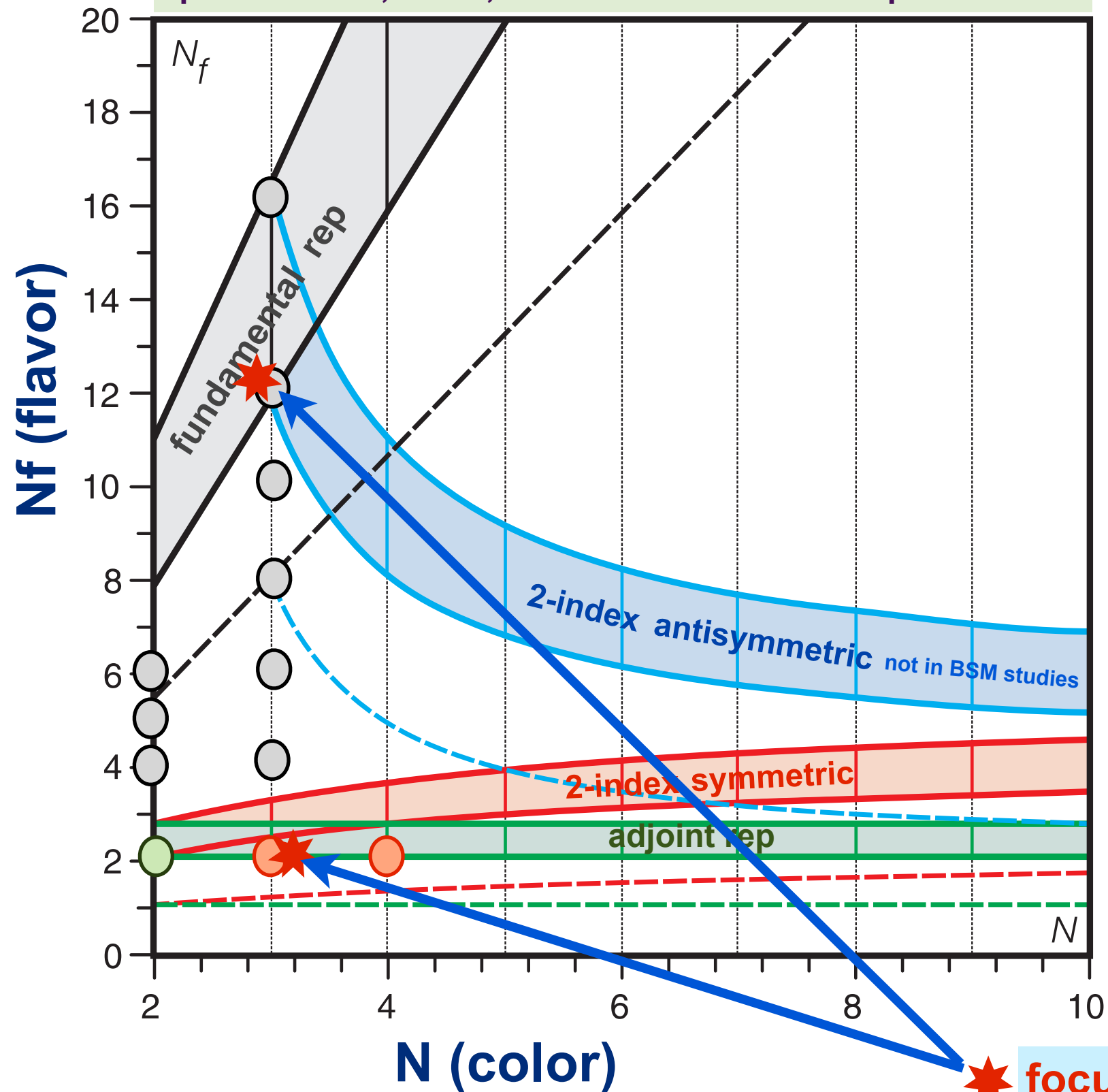
for each rep BSM interest is below conformal window but close to it:



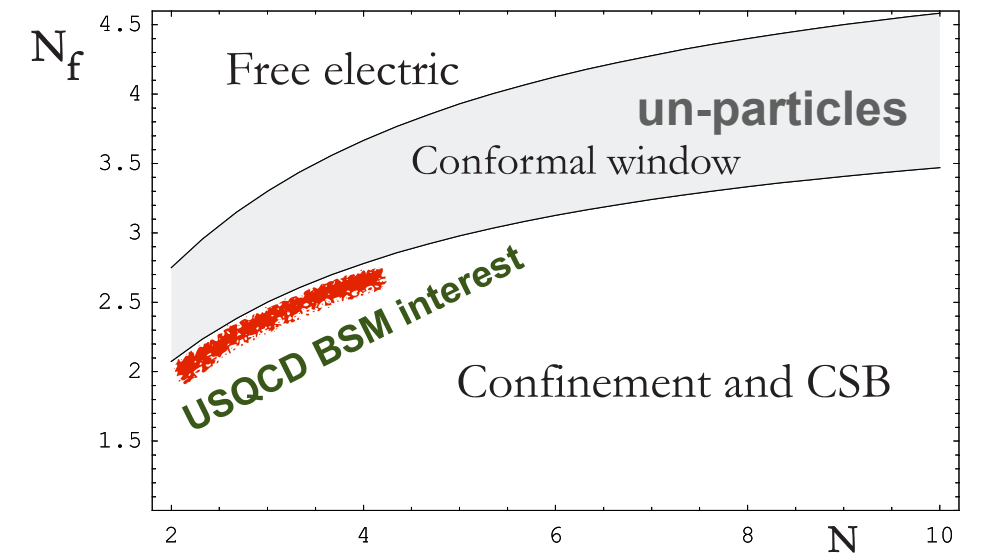
- USQCD BSM results of last 12 months in 3 reps including new projects just starting
- months in 3 reps including new projects just starting
- new projects just starting



**theory space and conformal window**  
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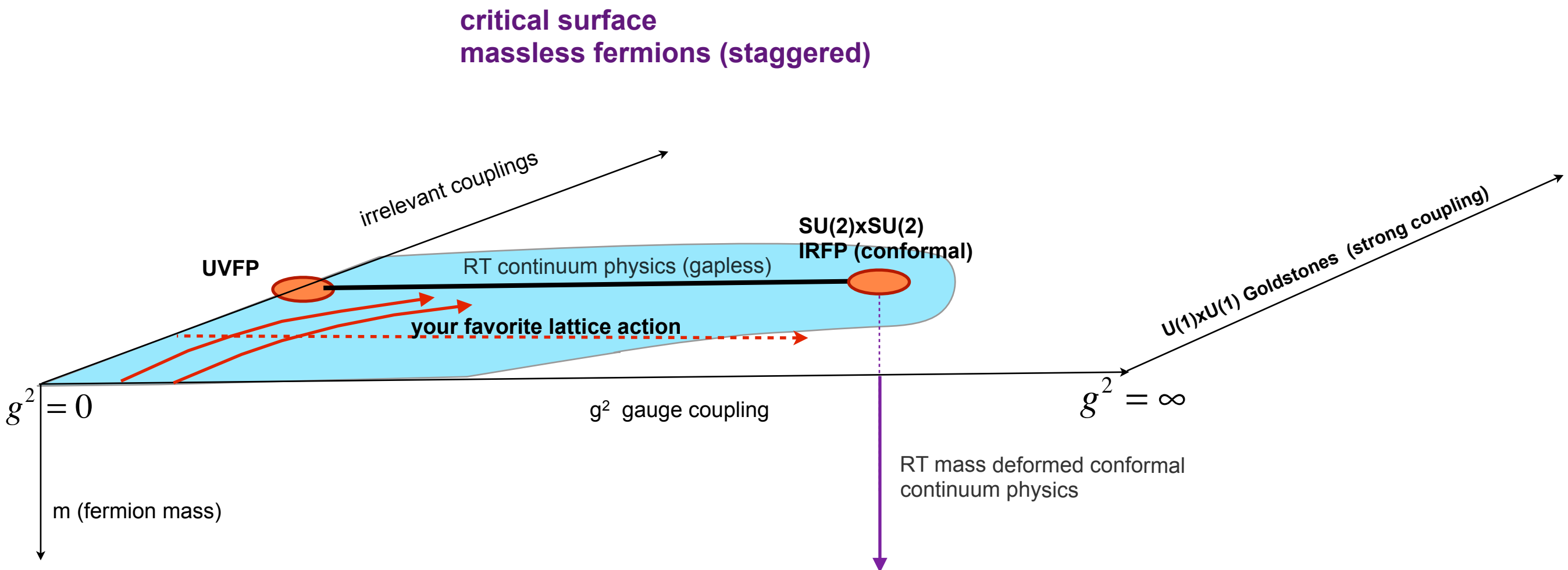
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★ **focus of this talk**

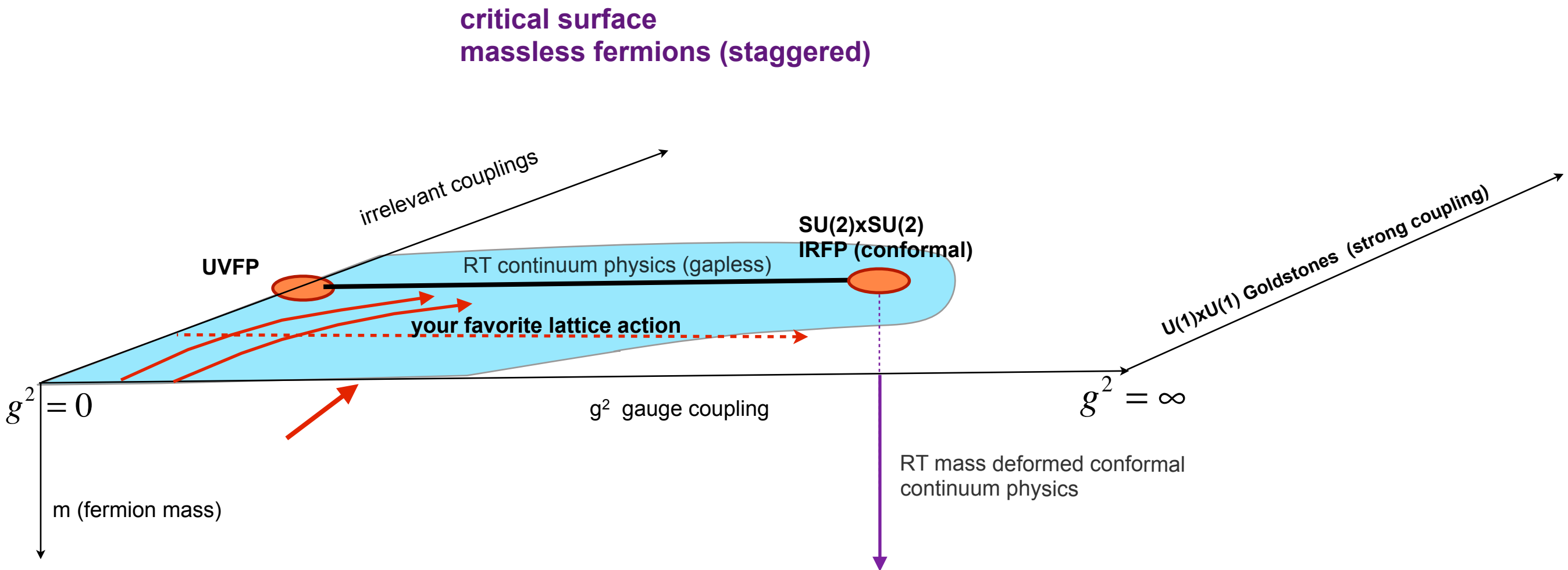
arXiv:1205.1878 [hep-lat]

**New extended data set and analysis**

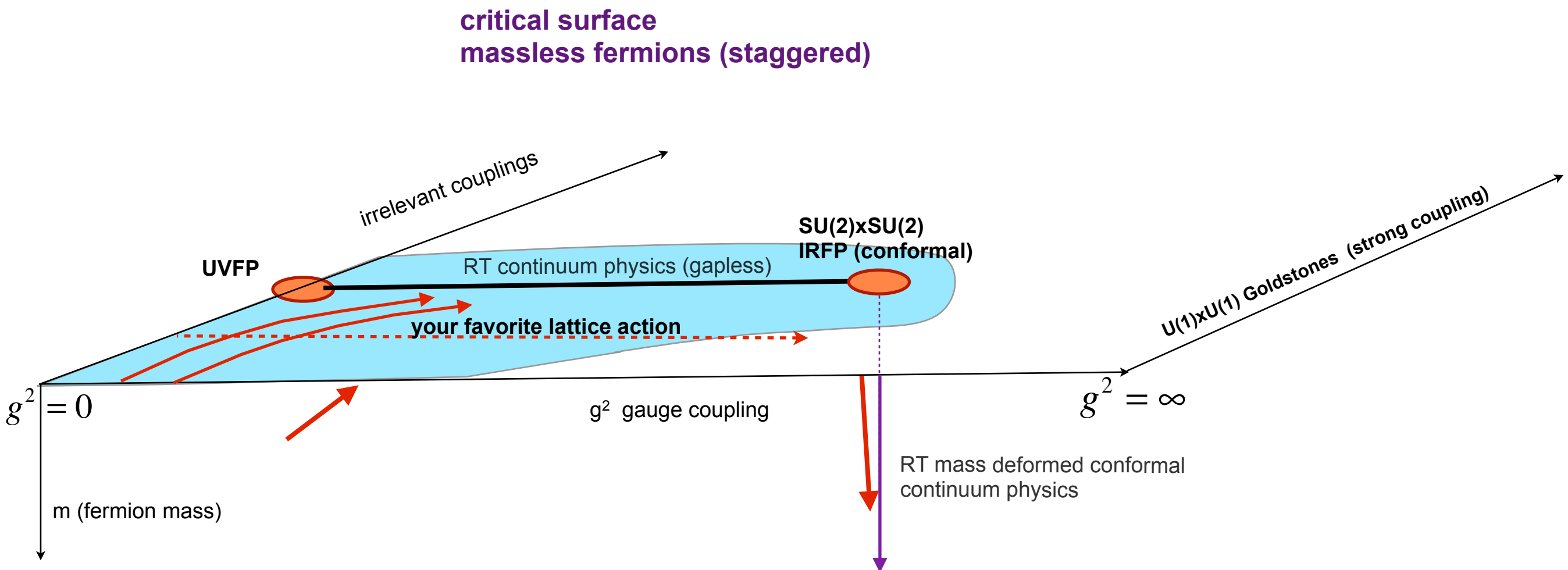
# Lattice navigation map



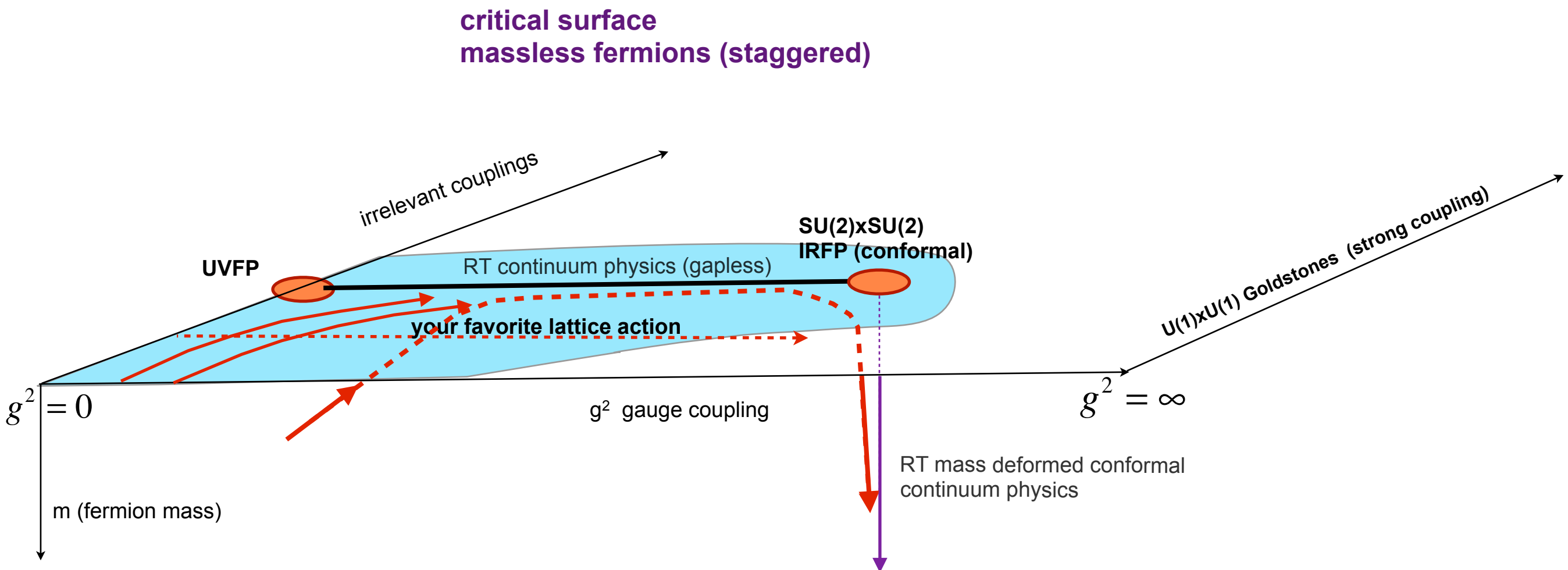
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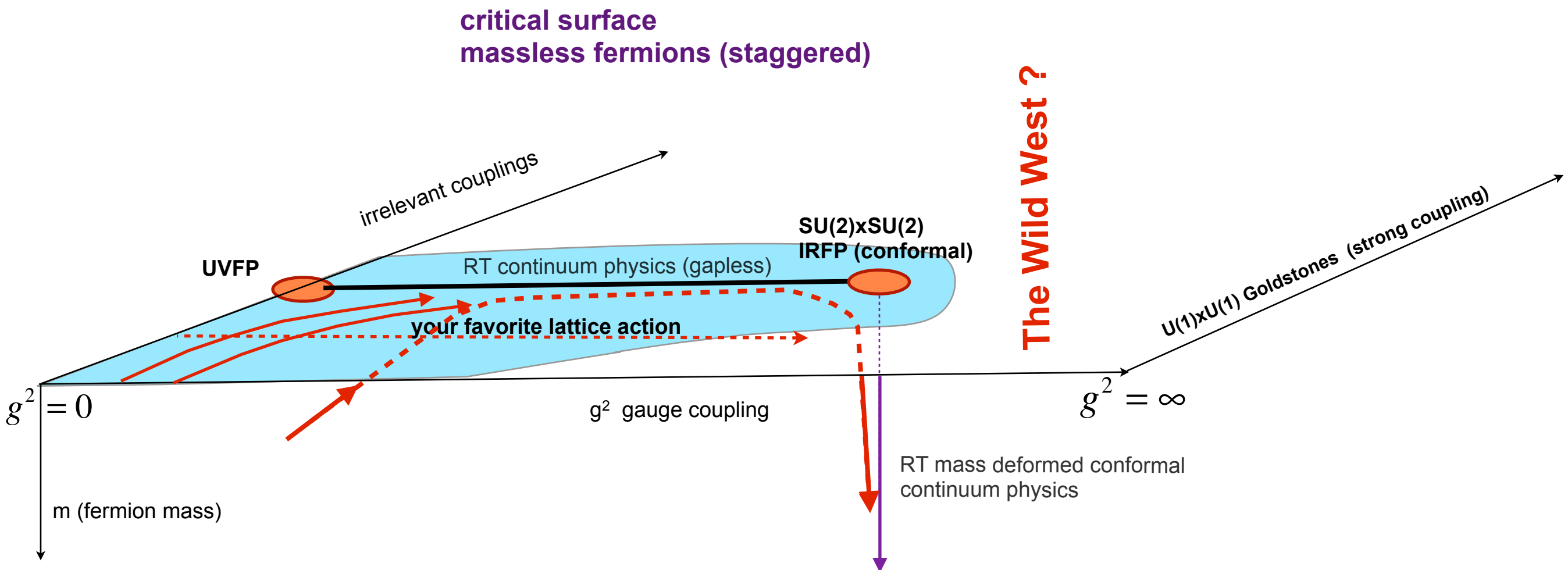
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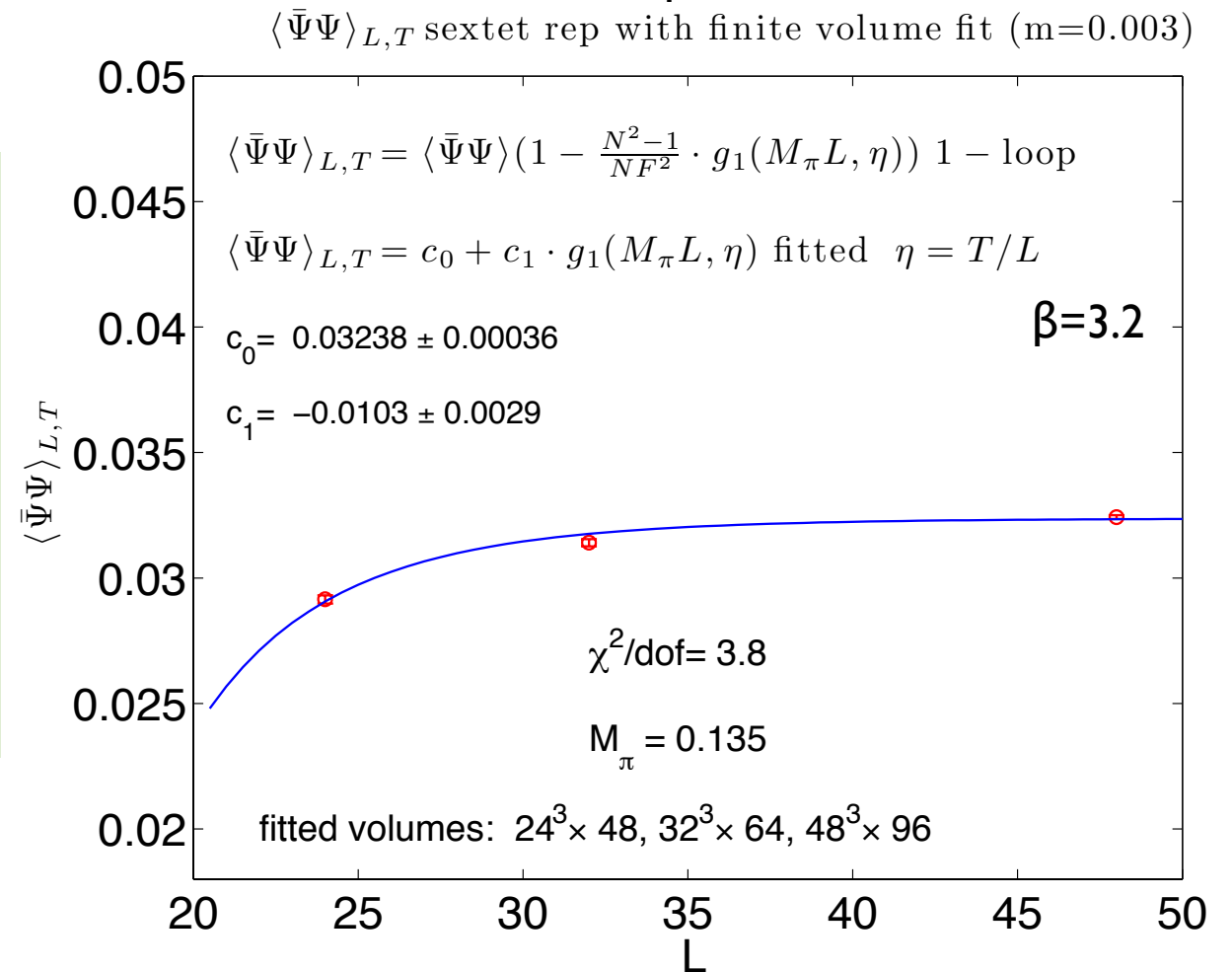
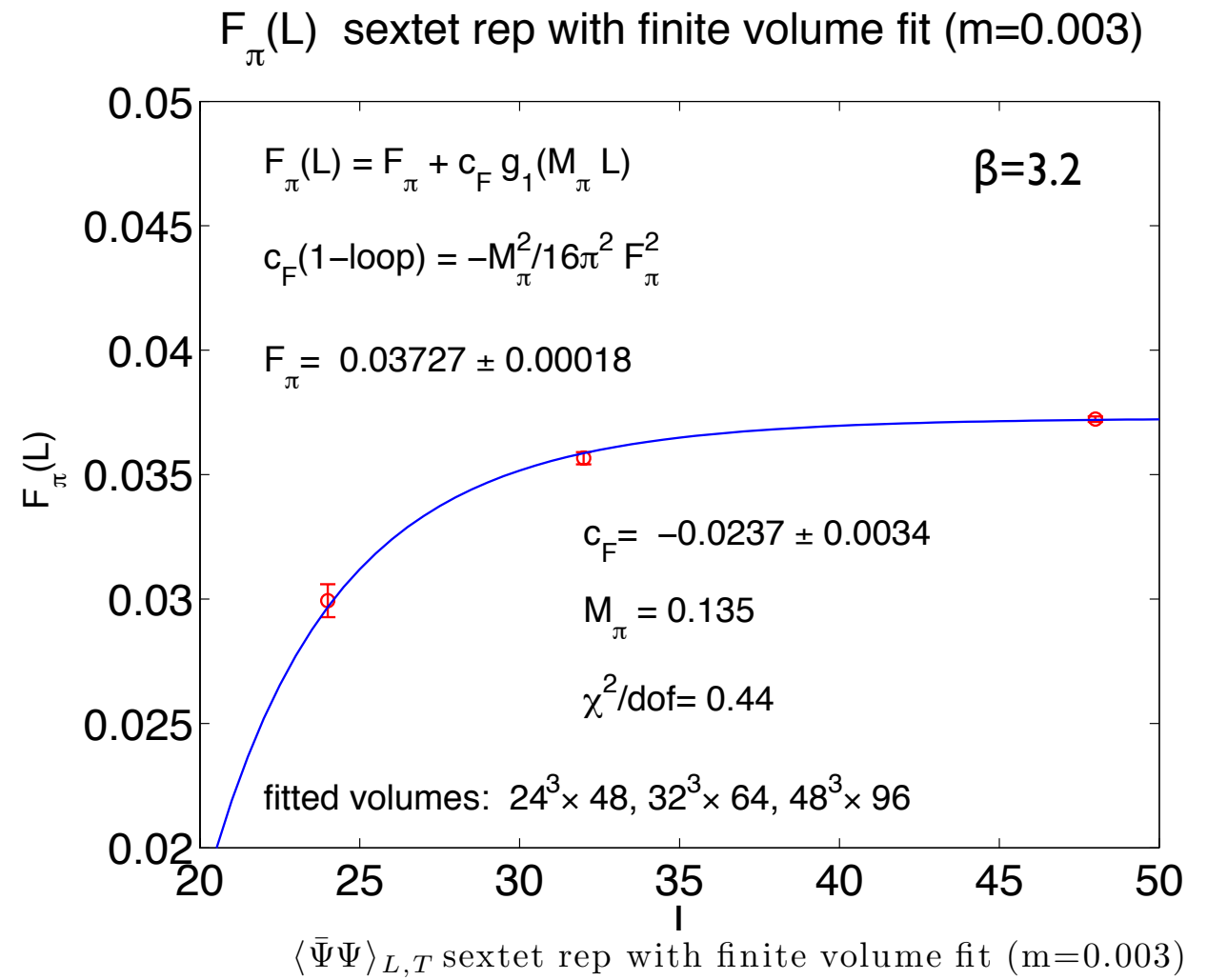
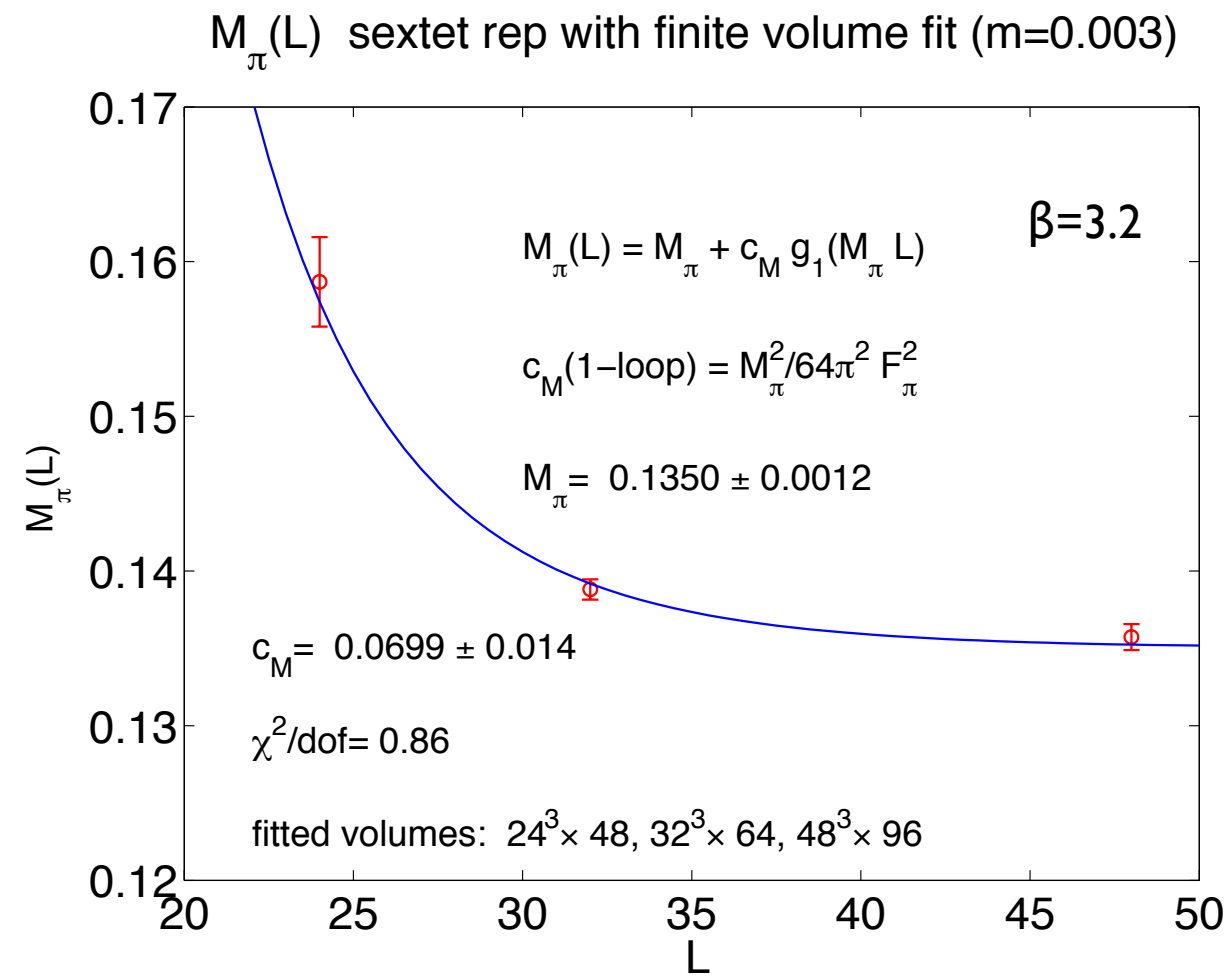
# status of $SU(3)$ $N_f=2$ sextet model

## minimal composite Higgs model?

our group: mass-deformed theory close to  $m=0$  critical surface and  $m \rightarrow 0$  limit:

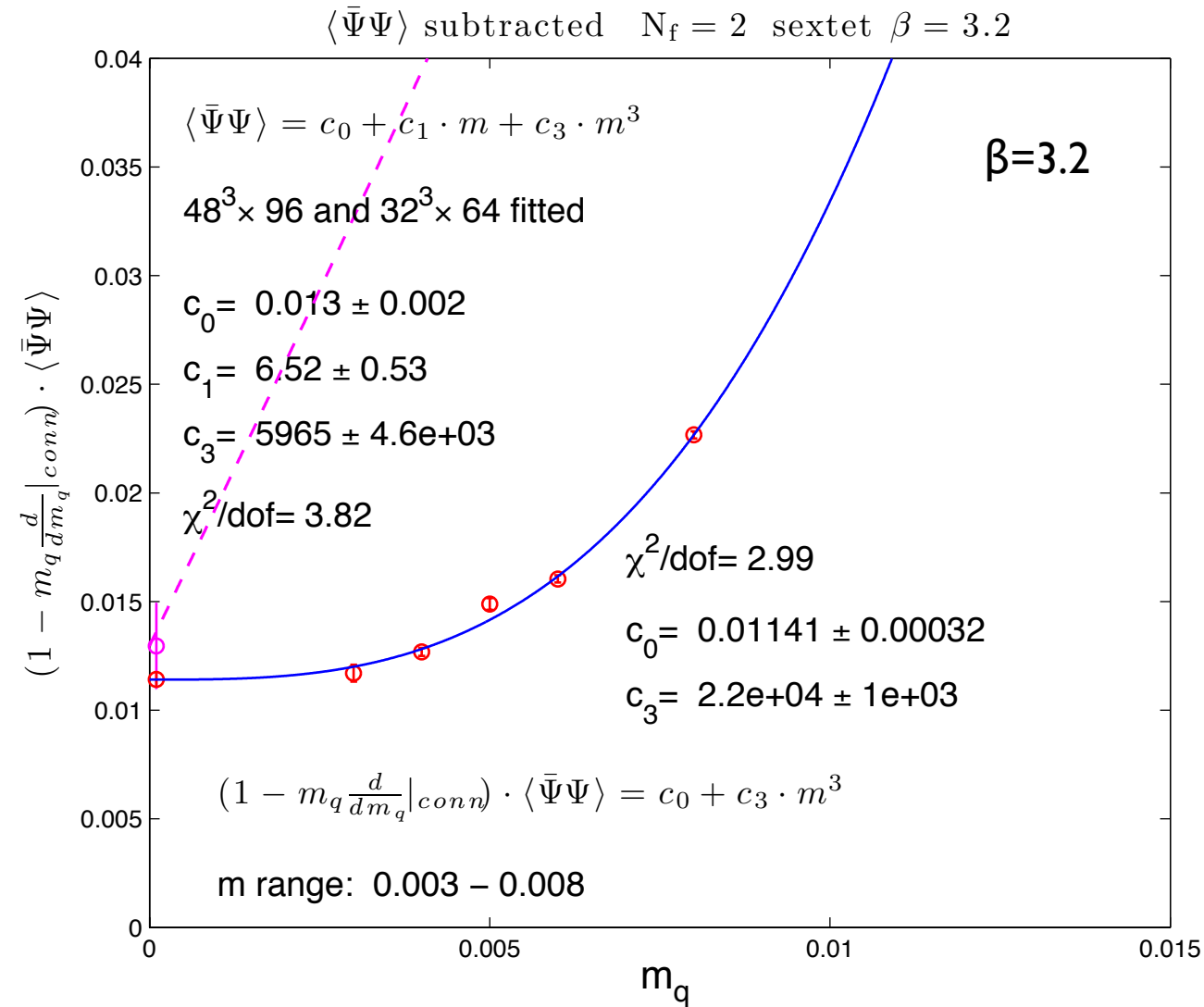
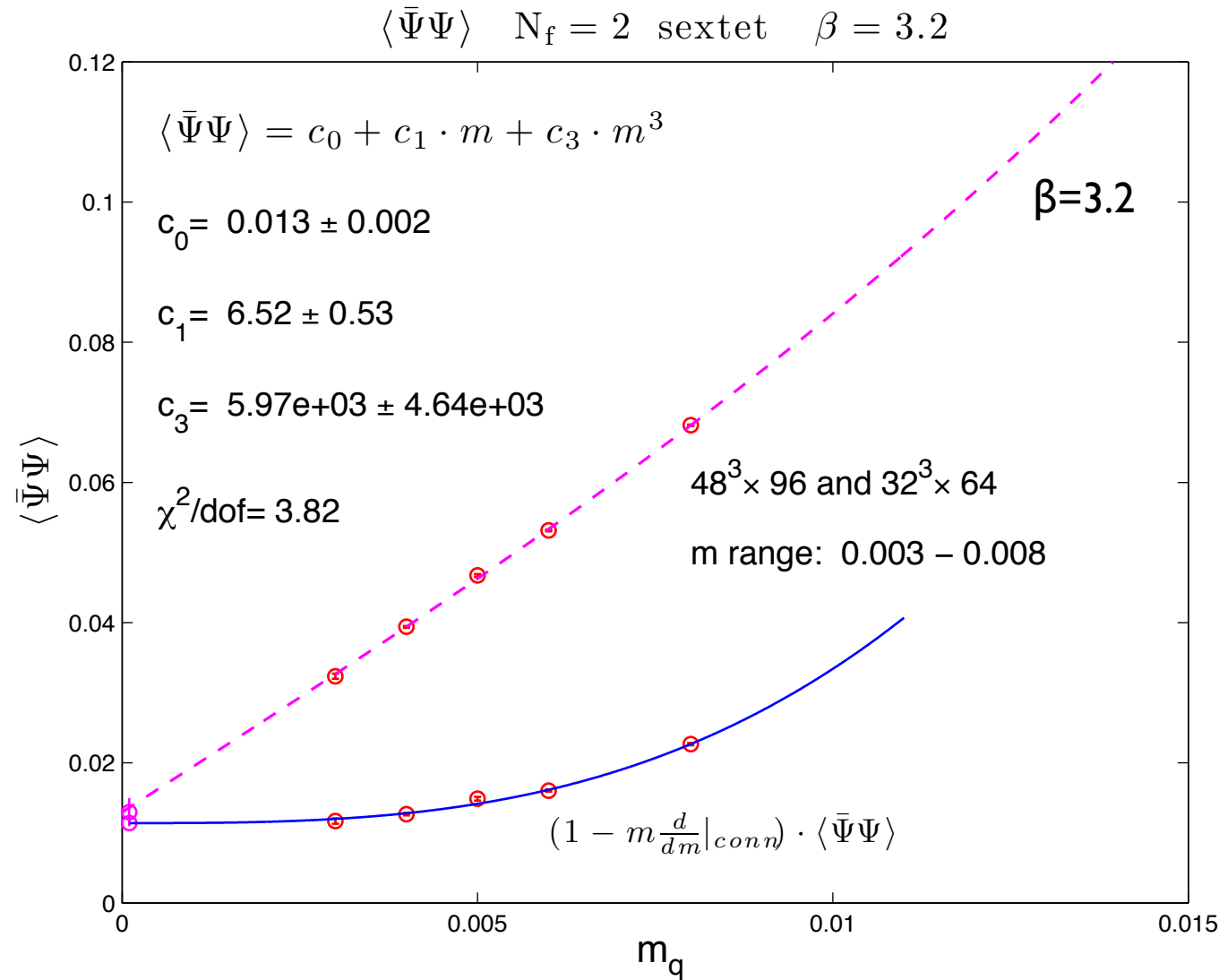
- two strategies complement: (1) inf volume conform scaling  
(2) mass-deformed FSS  
(1) is used in sextet model
- direct access to effective anomalous dimension  $\gamma$
- similar to tests of RG scaling laws of moments of current correlator functions  
(in progress)

mass-deformed theory  
 close to  $m=0$  critical surface  
 inf volume extrapolated chiral and  
 conform scaling tests in sextet model  
 for  $L \cdot M_\pi > 5$  one percent level reached





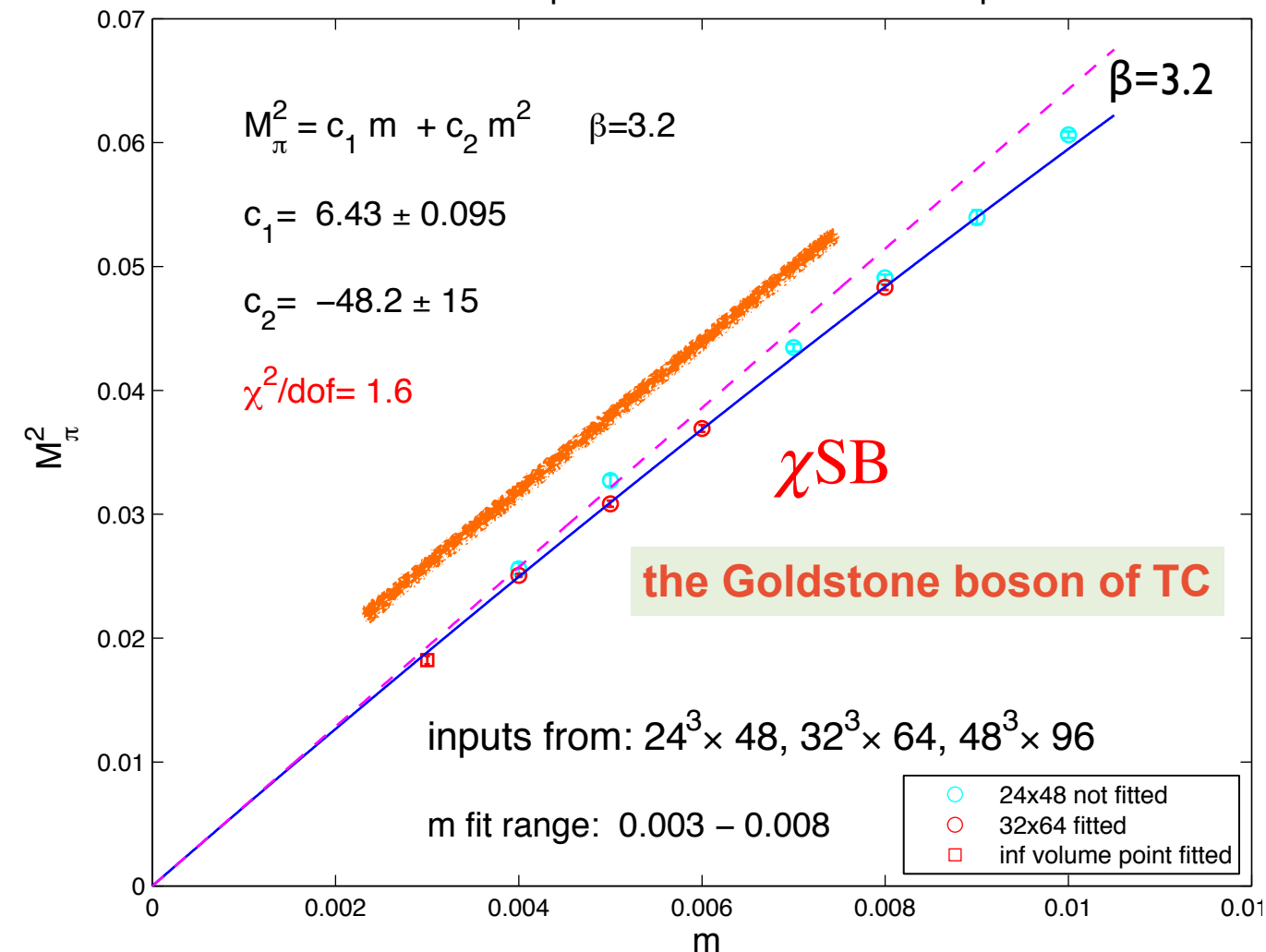
# Nf=2 SU(3) sextet chiral condensate



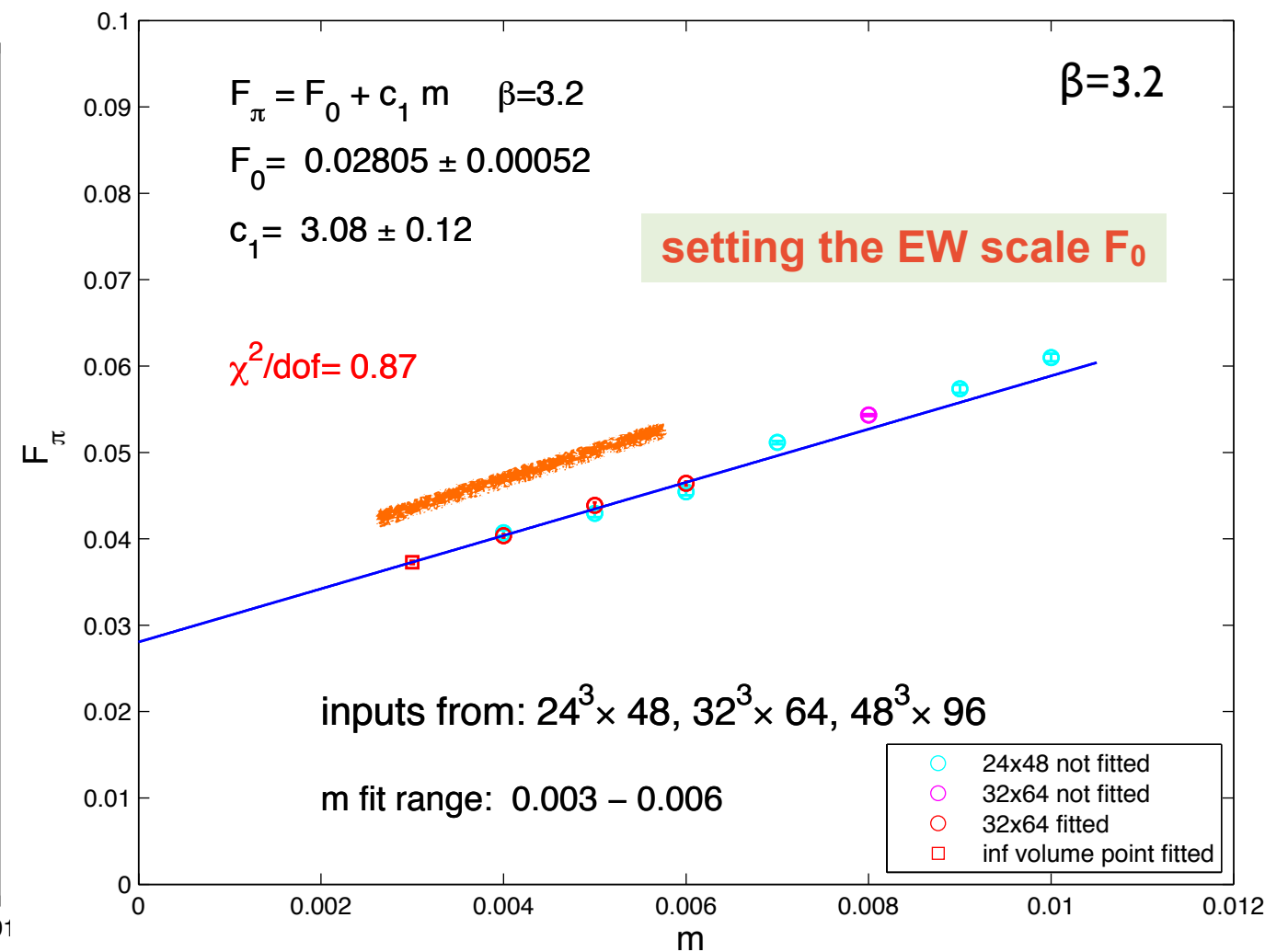
- two independent determinations of the chiral condensate
- consistently non-vanishing in chiral limit
- all sextet results are treated as inf volume (only  $m=0.003$  is truly extrapolated)

# Nf=2 SU(3) sextet chiral fits $M_\pi$ and $F_\pi$

sextet model Goldstone pion in PCAC channel with quadratic chiral fit



sextet model  $F_\pi$  in PCAC channel with linear chiral fit

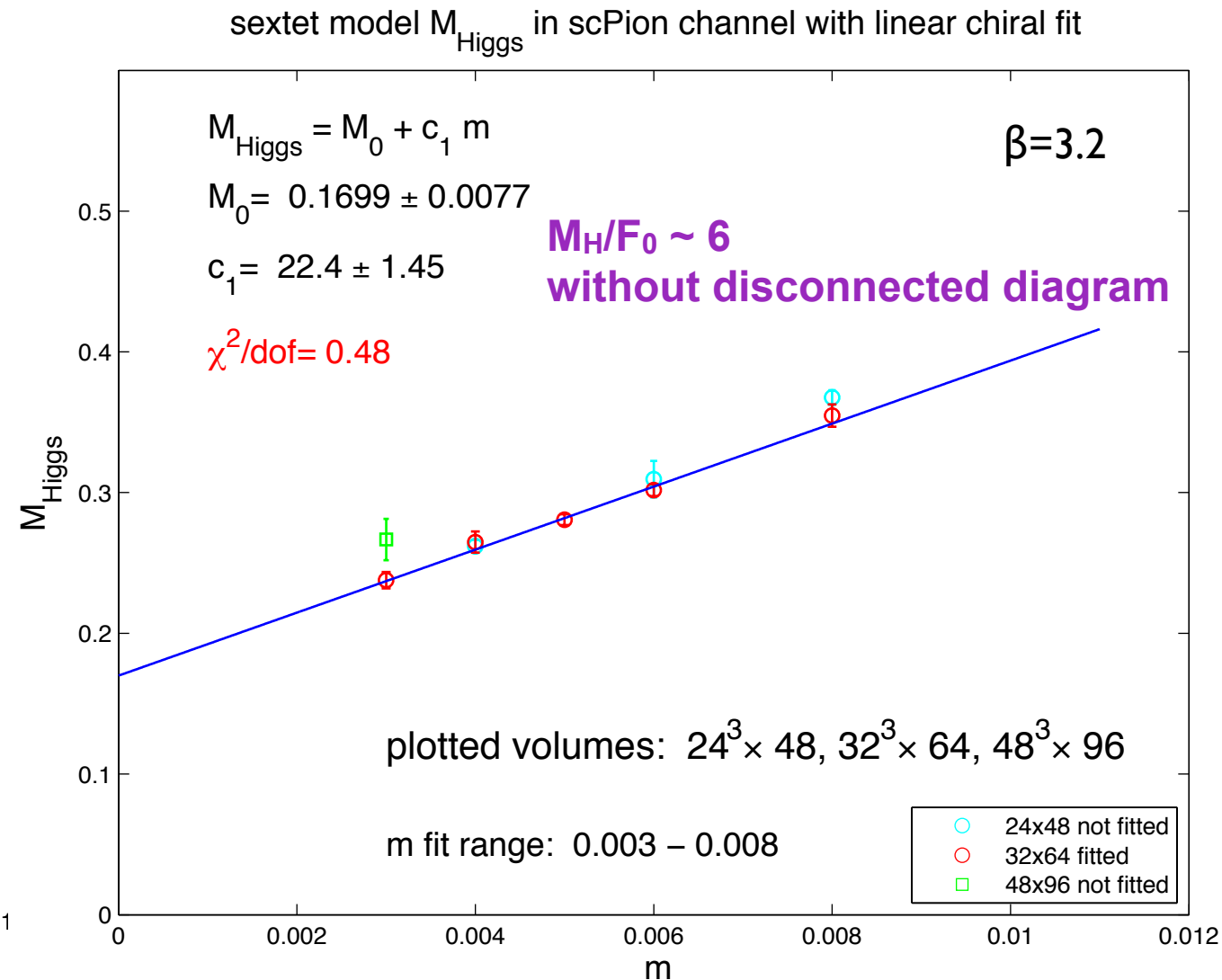
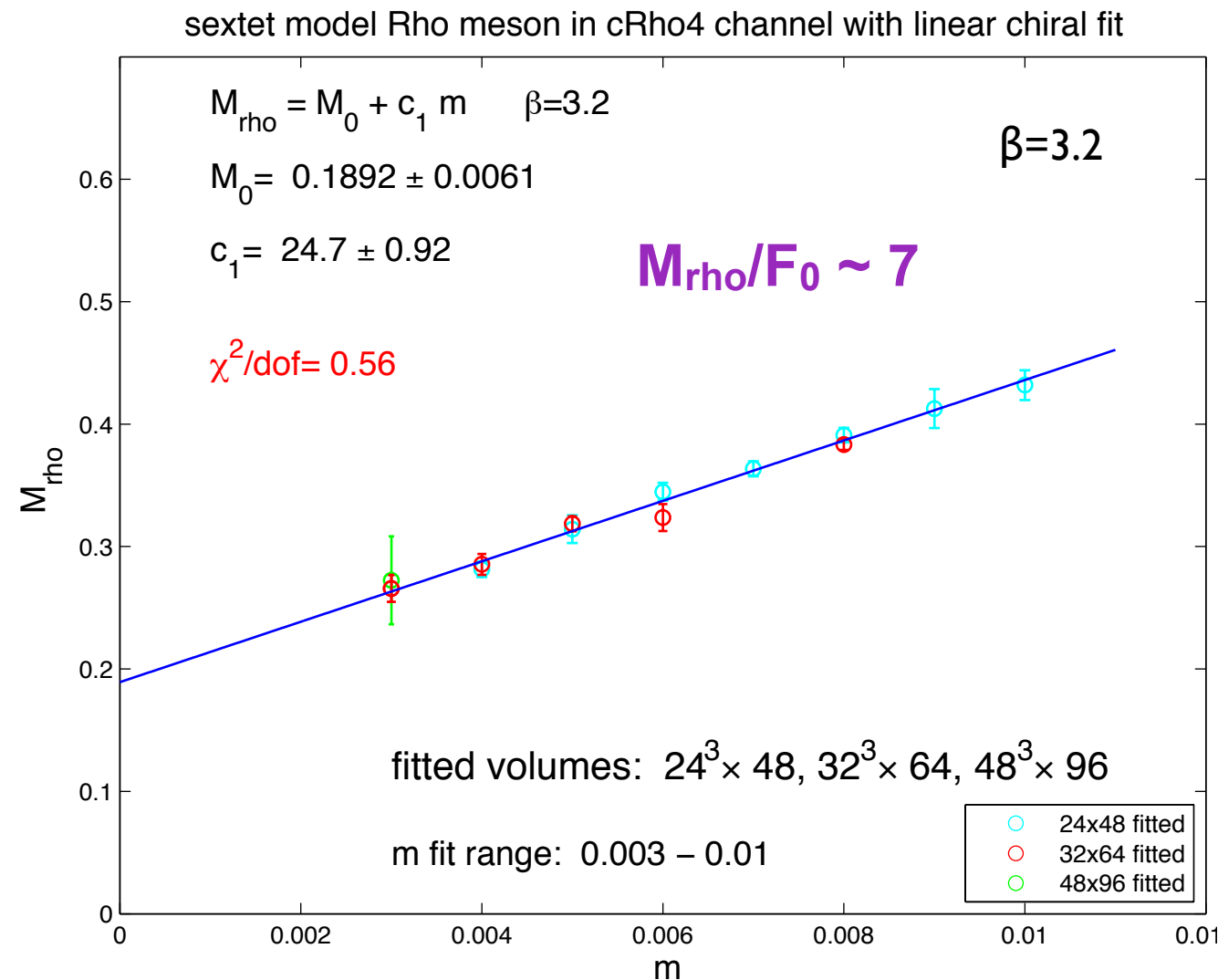


$m=0.003-0.006$  range close to chiral log regime?

Nf=2 helps!

log detection will require even more precise data

# Nf=2 SU(3) sextet chiral fits $M_\rho$ and $M_H$



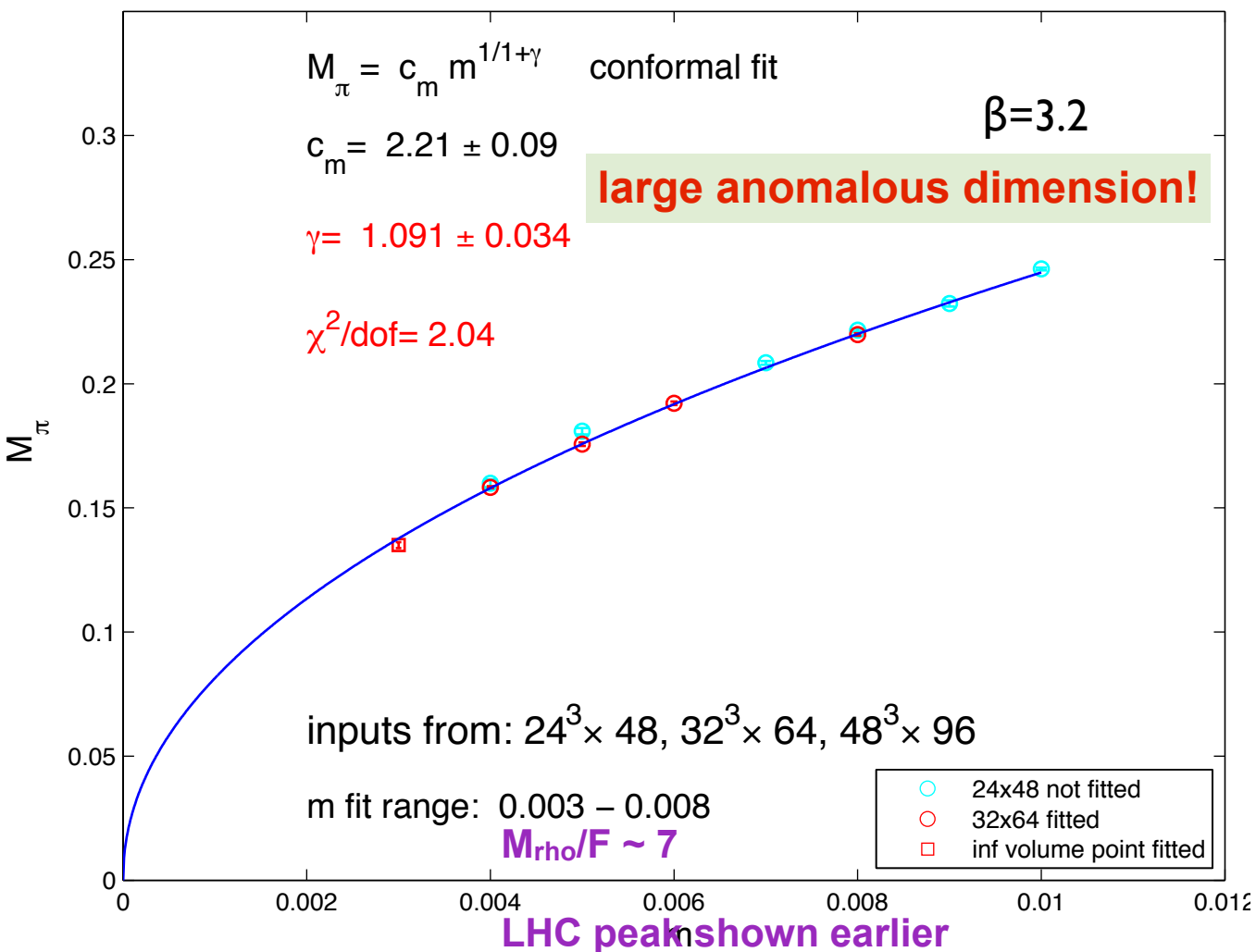
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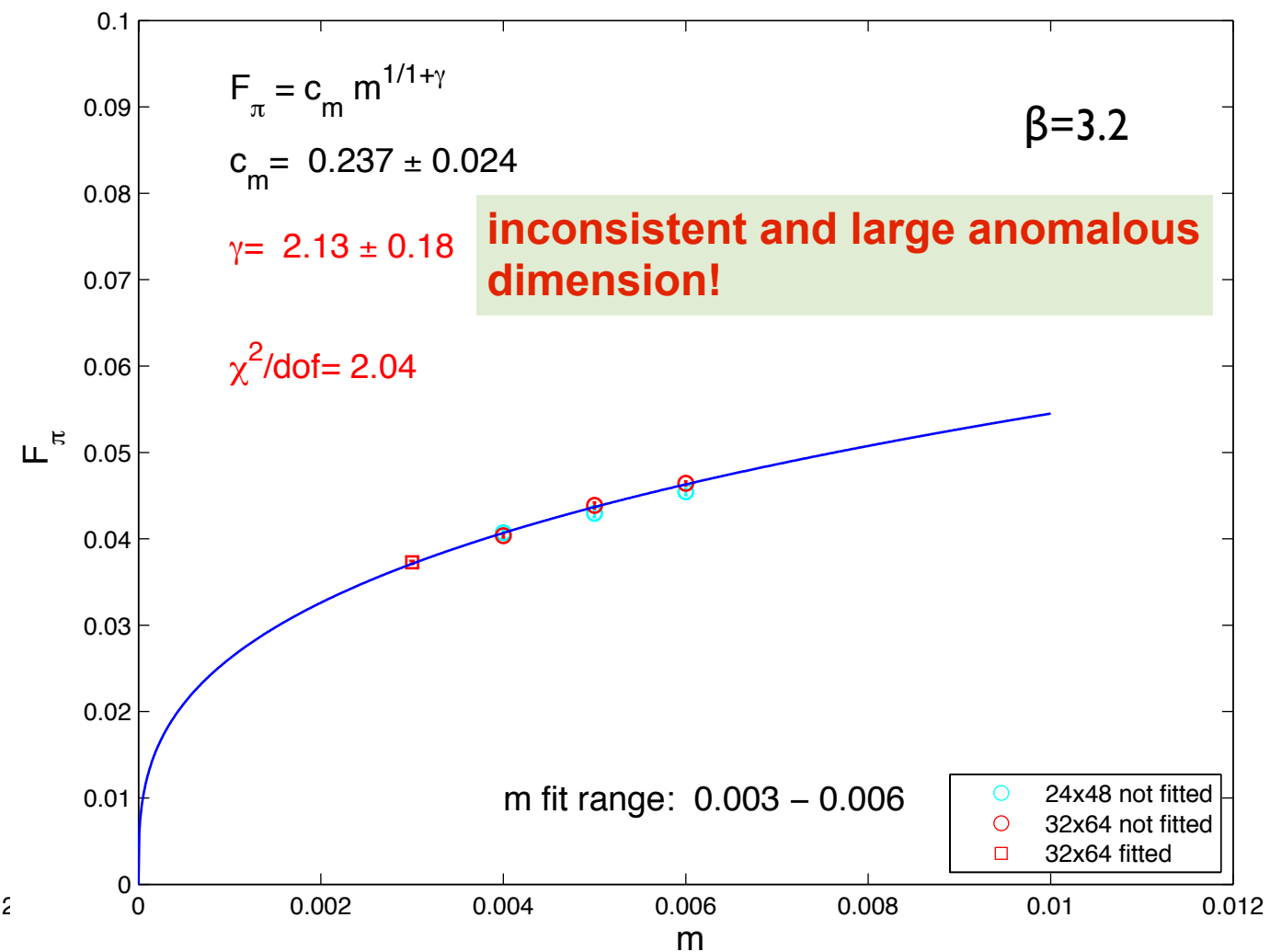
log detection will require even more precise data

# conformal hypothesis breaks down in global fits:

sextet model Goldstone pion in PCAC channel with conformal fit

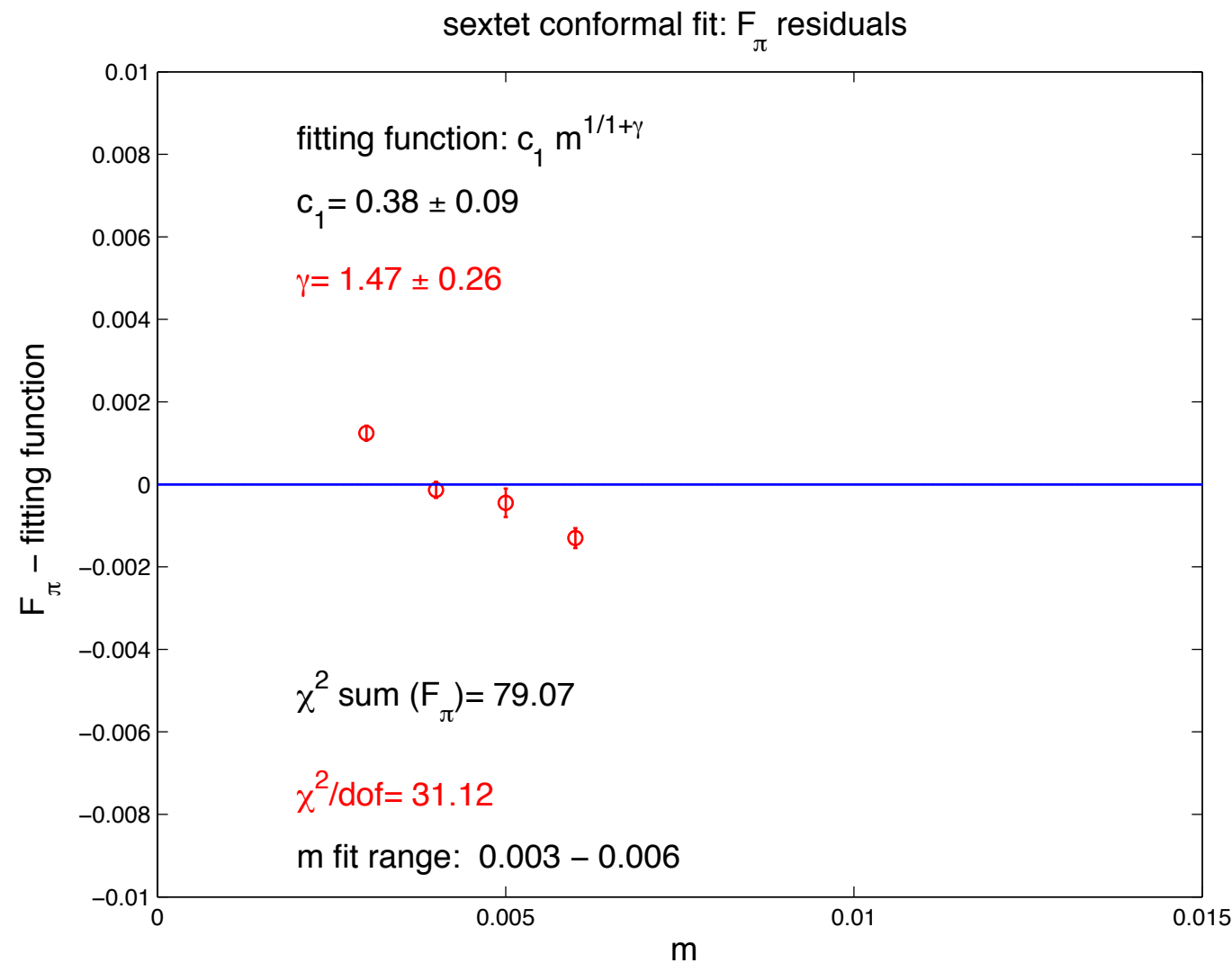
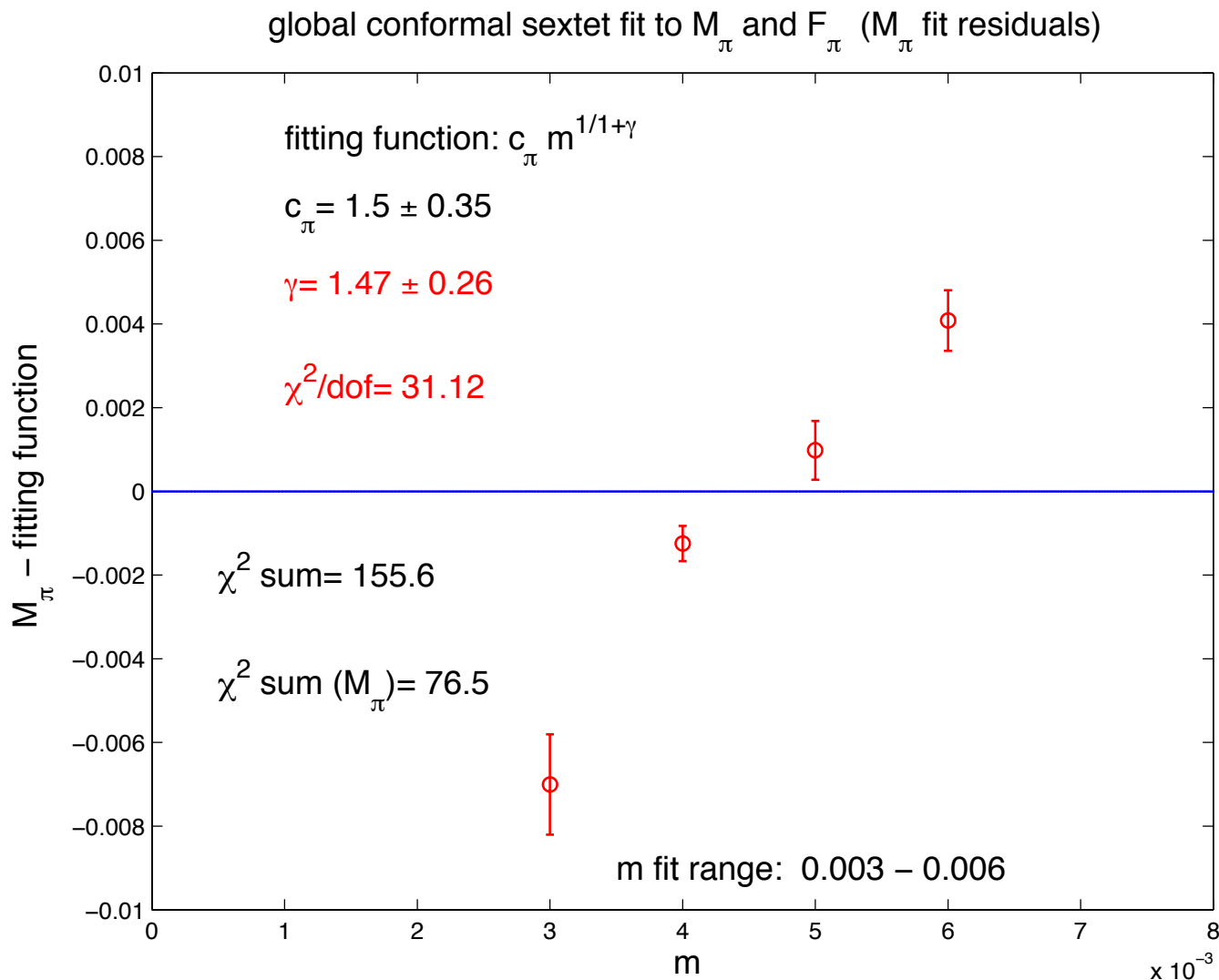


sextet model  $F_\pi$  in PCAC channel with conformal fit



inconsistent large critical exponents  $\gamma$

# conformal hypothesis breaks down in global fits:



large and inconsistent critical exponents  $\gamma$

are we close enough to the critical surface?

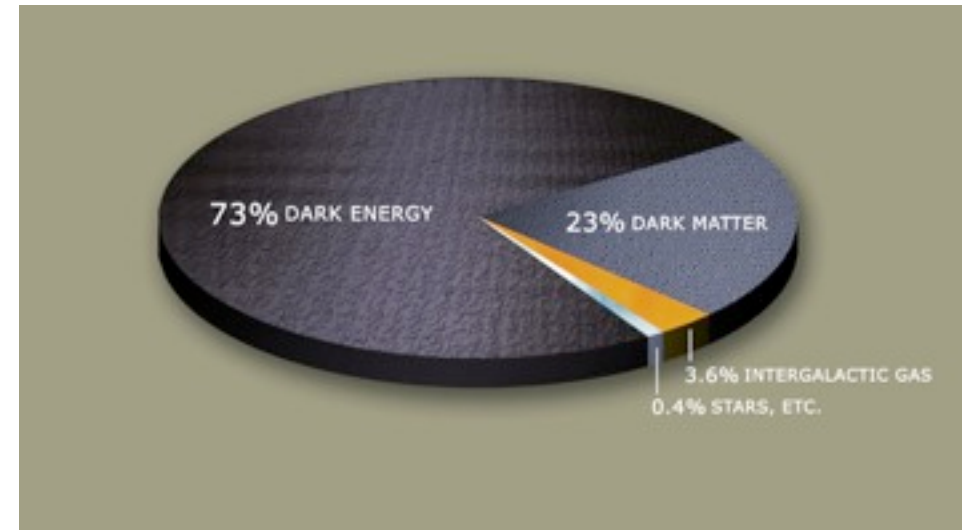
working on baryon spectrum

dark matter candidate

- lightest technibaryon can be stable by analog of  $U(1)_B$
- an initial matter/anti-matter asymmetry gets shared among baryons, leptons, technibaryons via sphalerons  
(Chivukula, Barr, Fahri, Nussinov)
- can get observed  $\Omega_{DM}/\Omega_B$  easily for  $\sim \text{TeV}$  scale DM  
must be electrically neutral, EW singlets to avoid direct detection  
Then leading operators are **charge radius** and **polarizability**:

ex.) 
$$\frac{B^* B v_\mu \partial_\nu F^{\mu\nu}}{\Lambda_{TC}^2}, \quad \frac{B^* B F_{\mu\nu} F^{\mu\nu}}{\Lambda_{TC}^3}$$

lattice input?

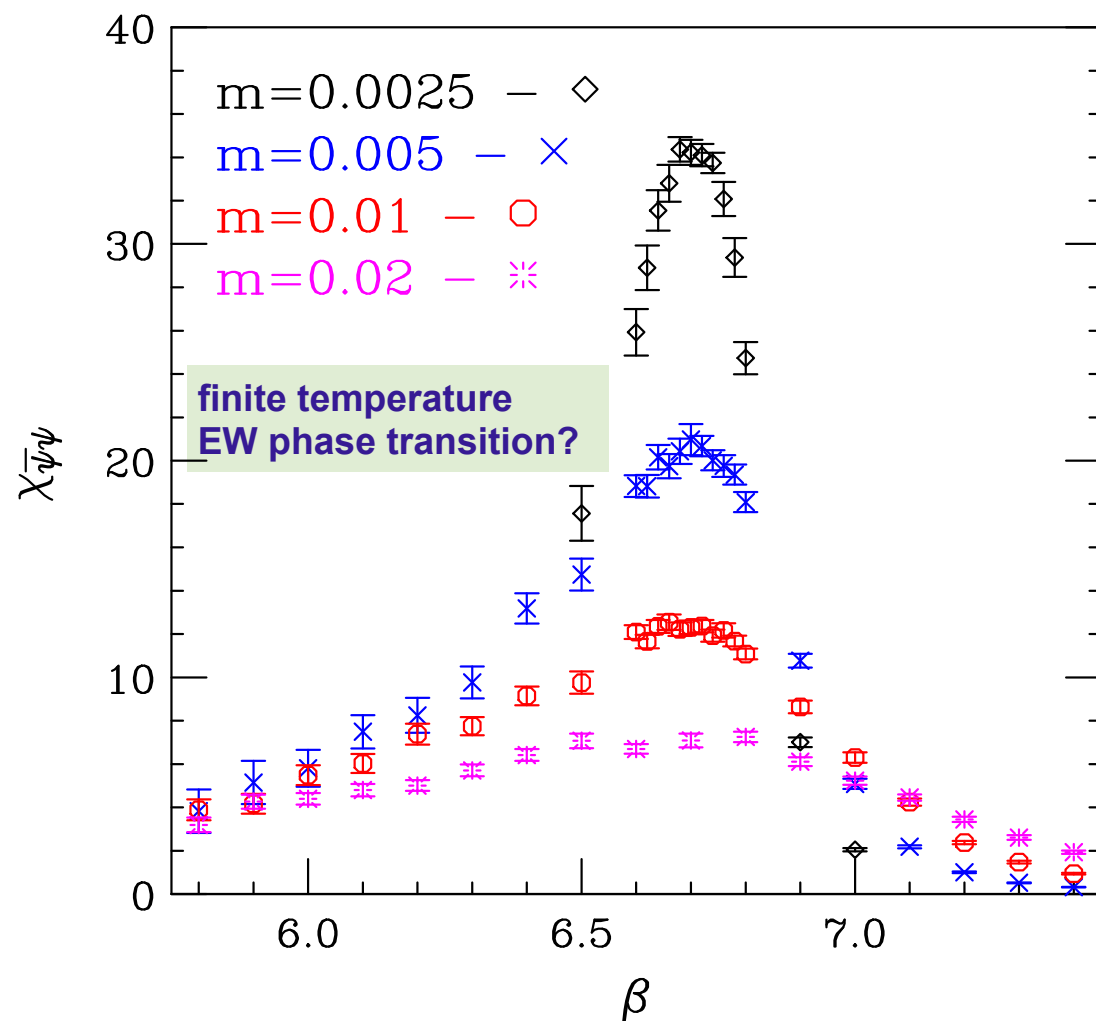


# EW phase transition in sextet Higgs model - early universe

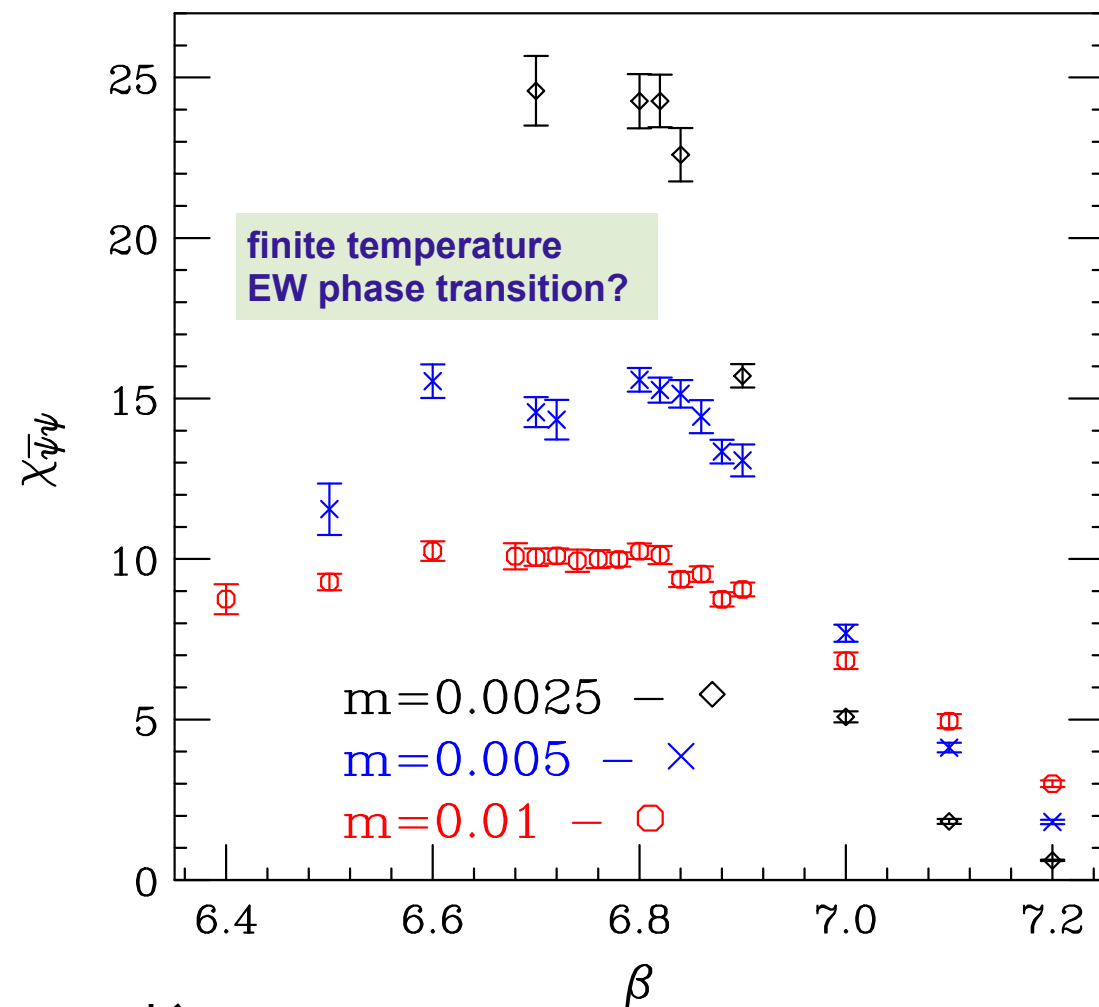
sextet model (*Kogut-Sinclair*)

*potential implications in early cosmology*

$16^3 \times 8$  lattice



$24^3 \times 12$  lattice

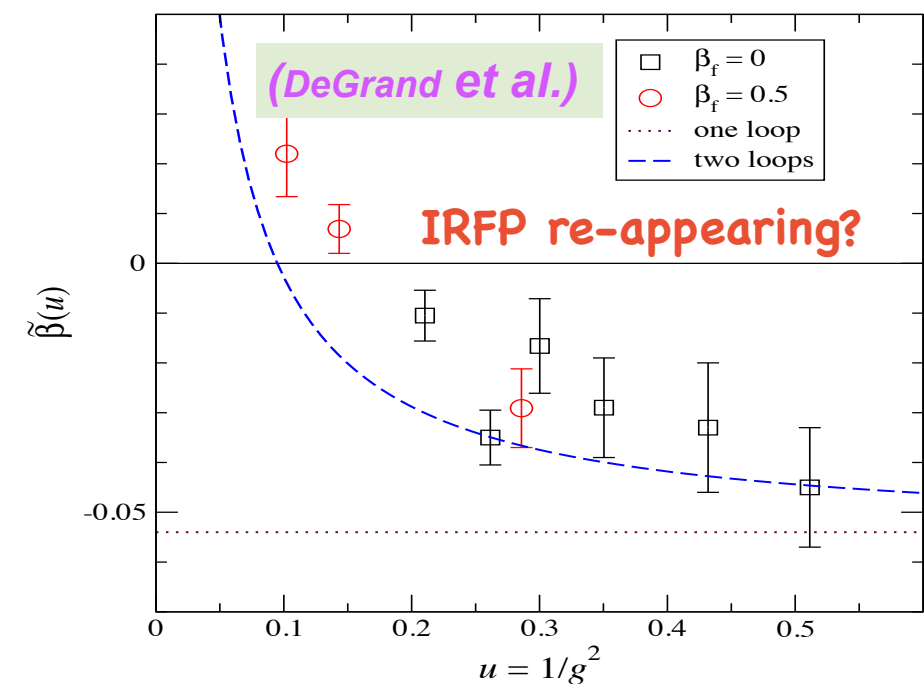
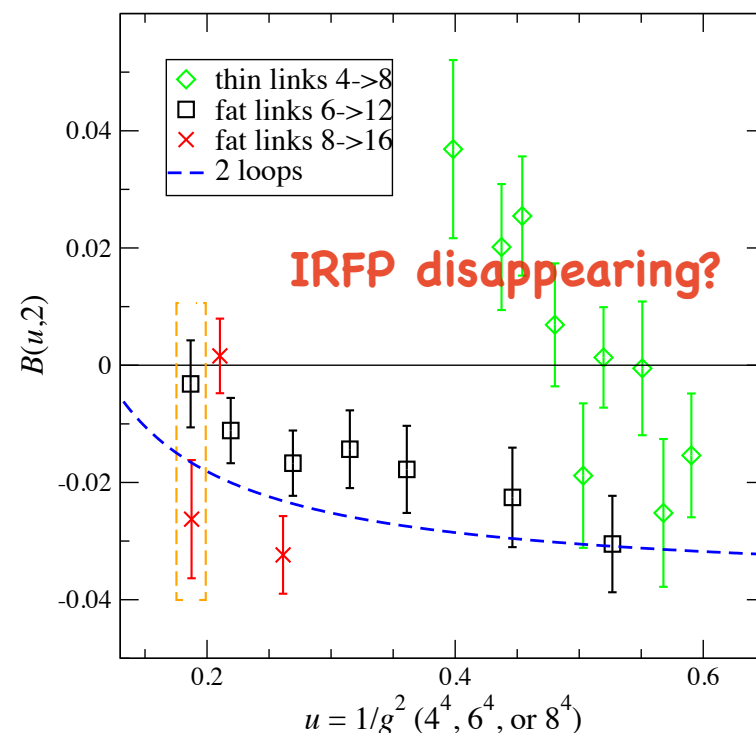


**Nf=2 SU(3) sextet rep summary:**



- No inconsistency with  $\chi^{SB}$  in Nf=2 SU(3) sextet model
- We find inconsistency with conformal symmetry in all tests
- The **effective** anomalous dimension is inconsistent and large  $\gamma$  is in 1-2 range
- Kogut and Sinclair: looking for finite temperature  $\chi^{SB}$  phase transition

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- DeGrand et al. find: Nf=2 sextet beta function might have an IRFP zero?
- uninteresting model with small anomalous dimension ?
- $\gamma < 0.45$  controversy is not resolved



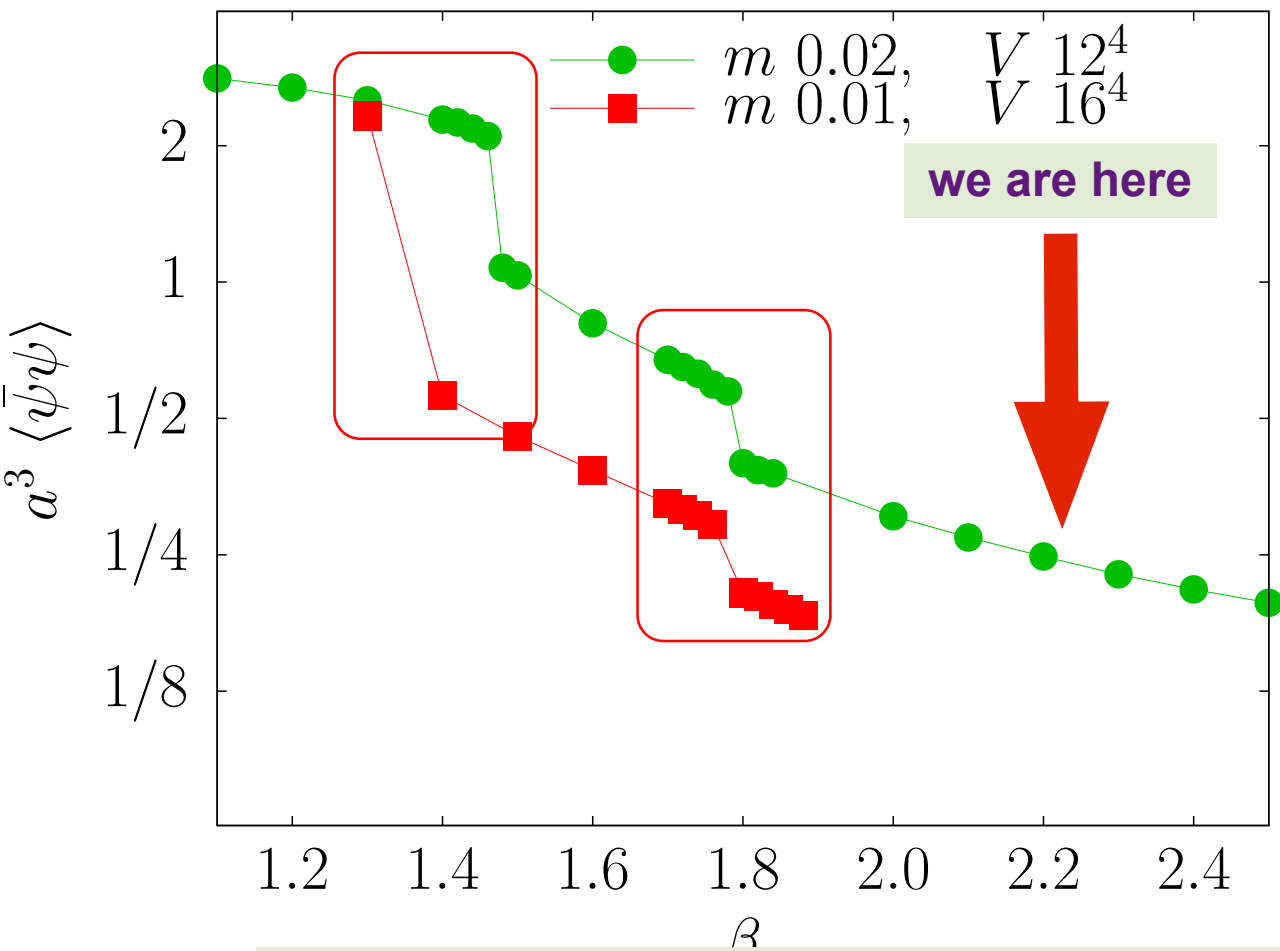
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 $\gamma < 0.45$  controversy is not resolved
- We expect: the Nf=2 sextet model with SU(3) color is an interesting candidate for the composite Higgs mechanism
- But viability requires confirmation, studies of the running coupling, the S-parameter, and composite Higgs physics

# status of $SU(3)$ $N_f=12$ fundamental rep

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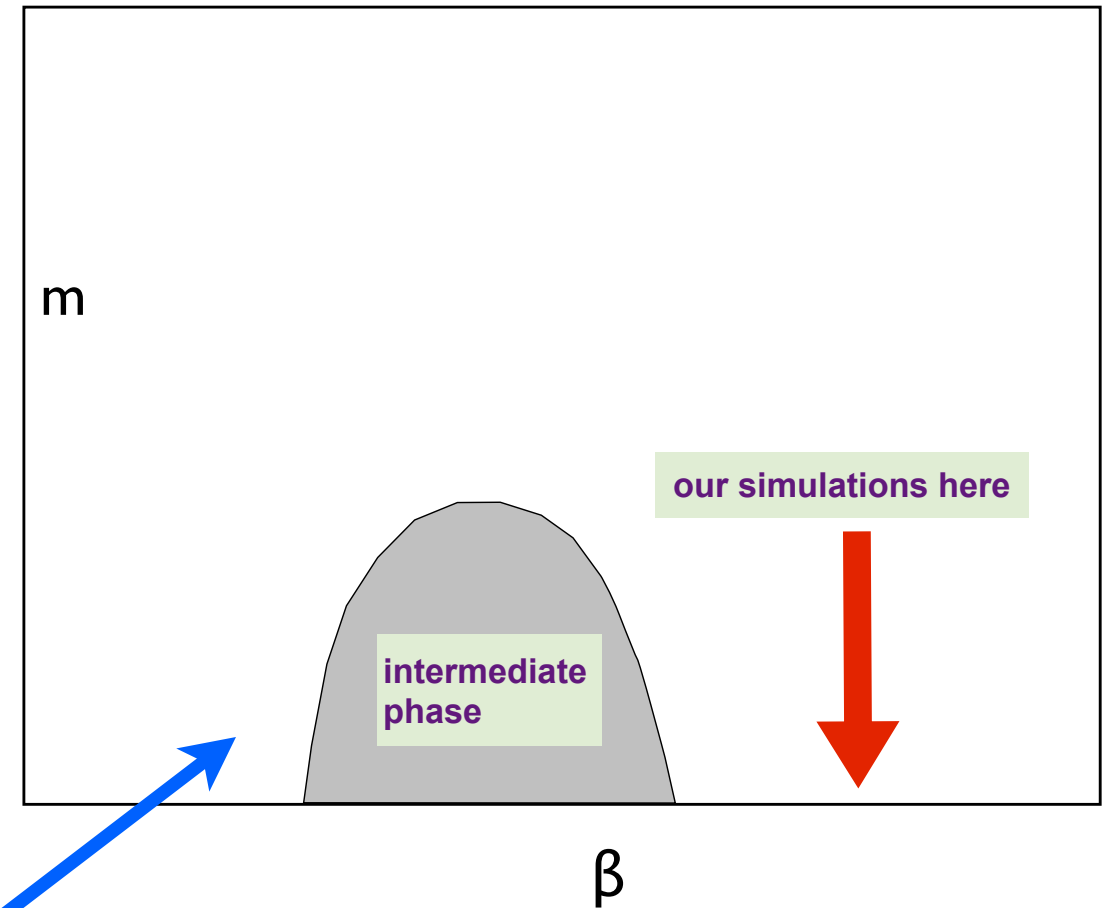
- two strategies complement: (1) inf volume conform scaling  
(2) mass-deformed FSS  
(2) is used in  $N_f=12$  fundamental  $SU(3)$  rep
- direct access to some effective anomalous dimension
- similar to tests of RG scaling laws of moments of correlator functions (in progress)

# bulk transition? (Schroeder, Latt 2011)



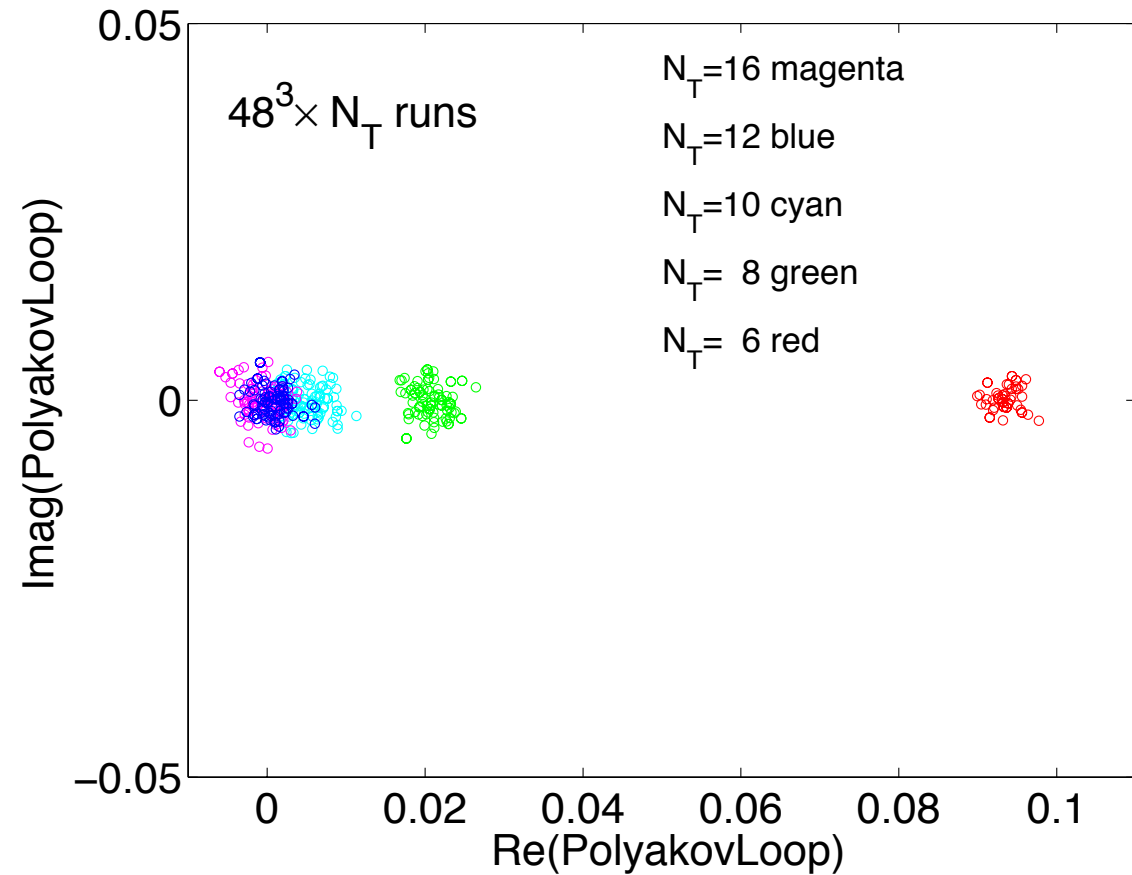
Deuzeman et al. new study

A. Hasenfratz et al. new study

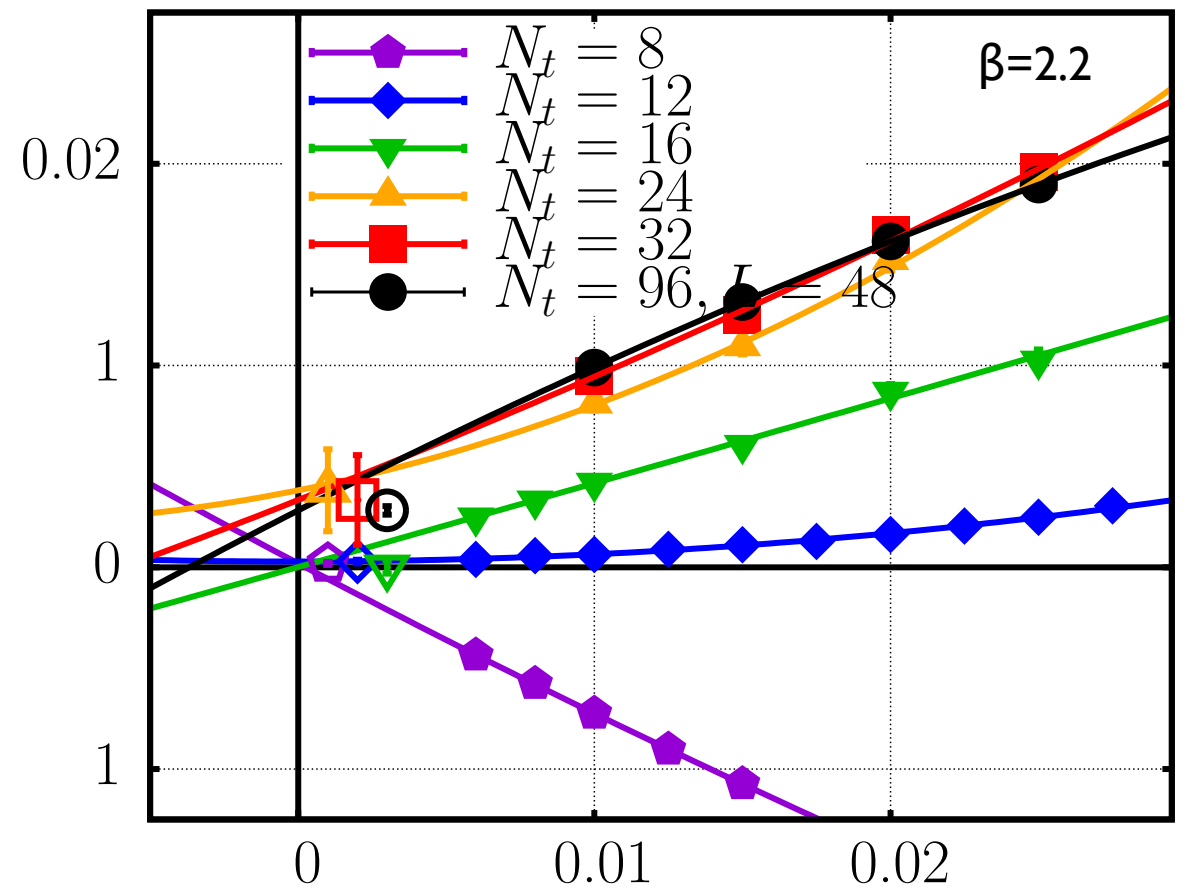
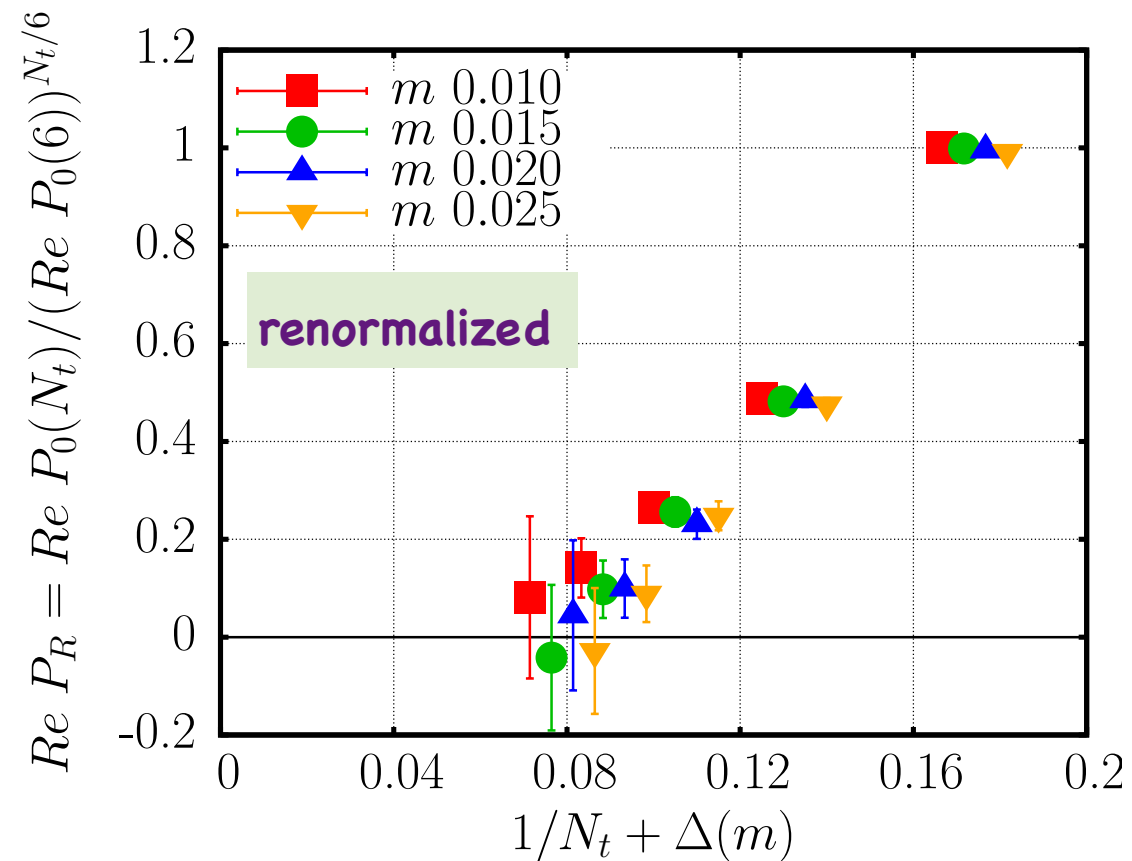


Our simulation are not effected

Polyakov loop scatter plot at finite temperatures



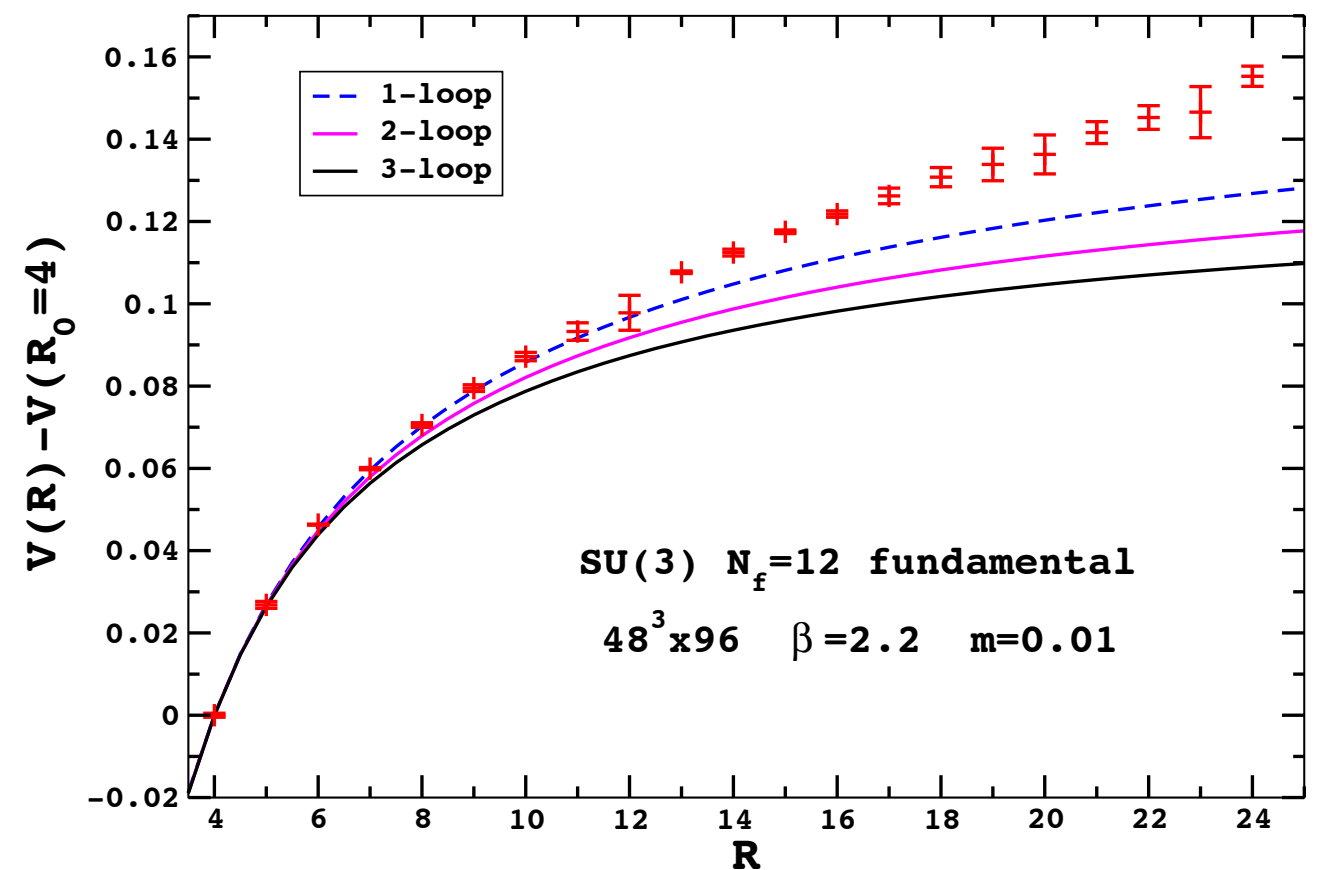
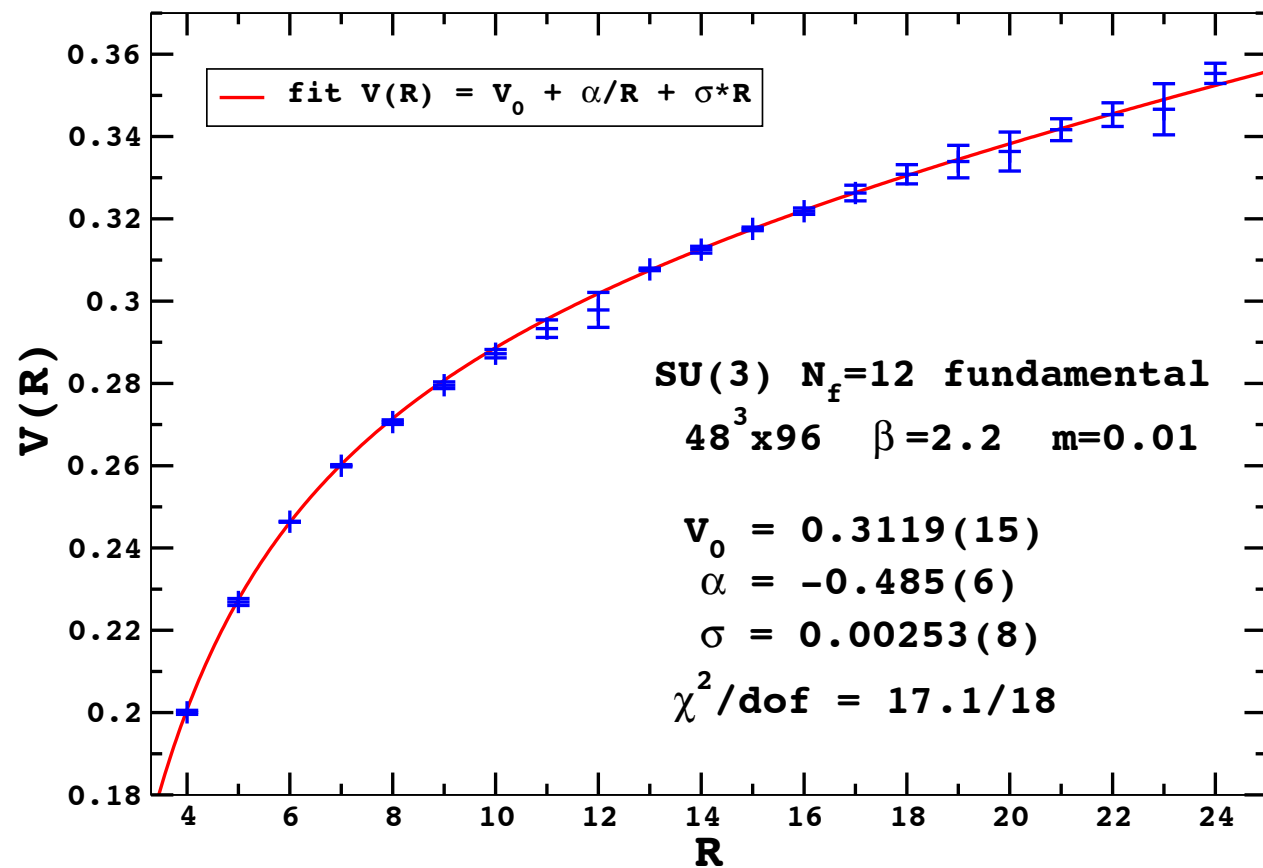
finite T transition at  $\beta=2.2$ ?



$48^3 \times N_t$  sequence  
(Schroeder, Latt 2011)

$Re P$  approaches zero at low temperature

# zero temp confinement – running coupling without IRFP ?

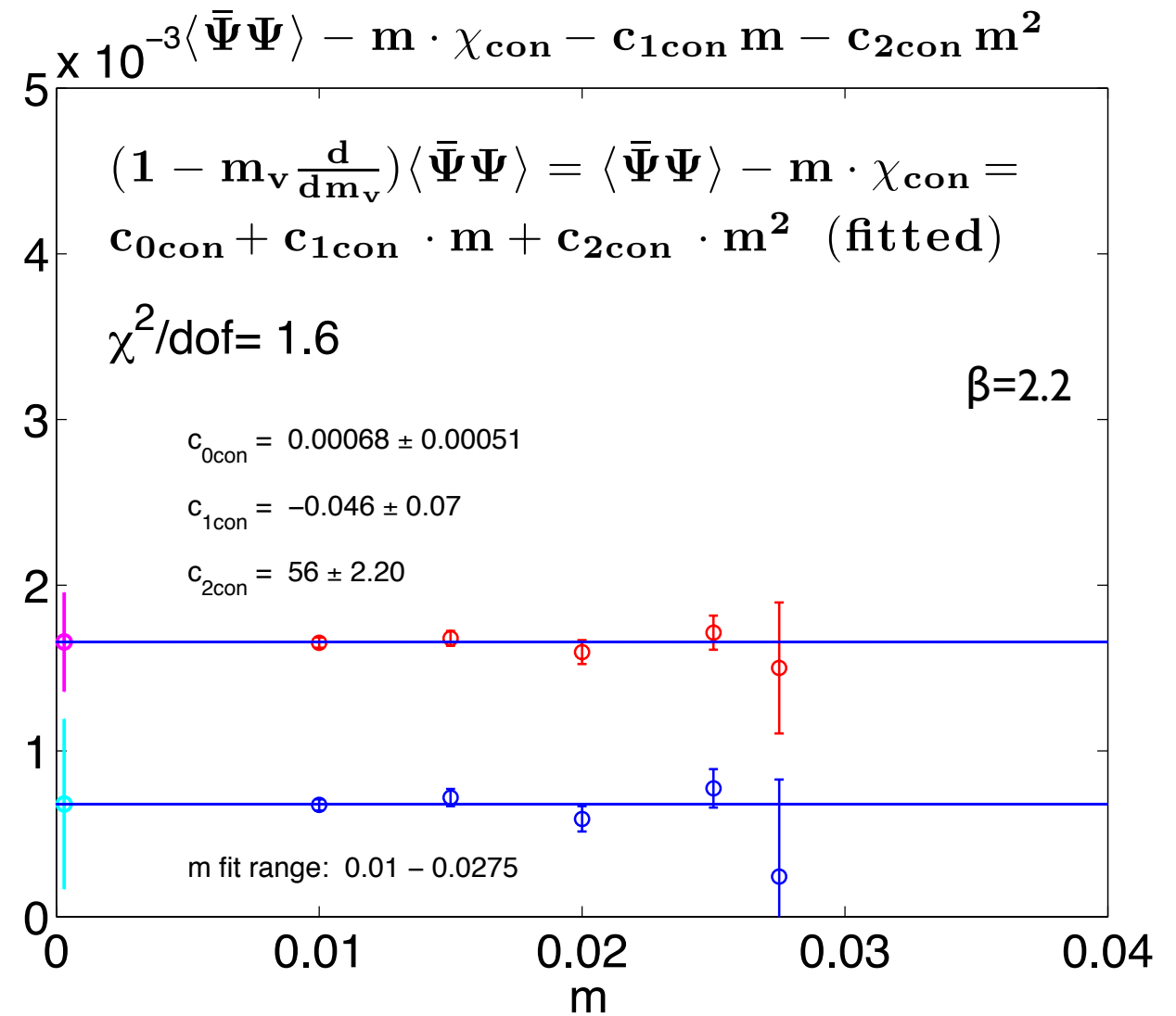
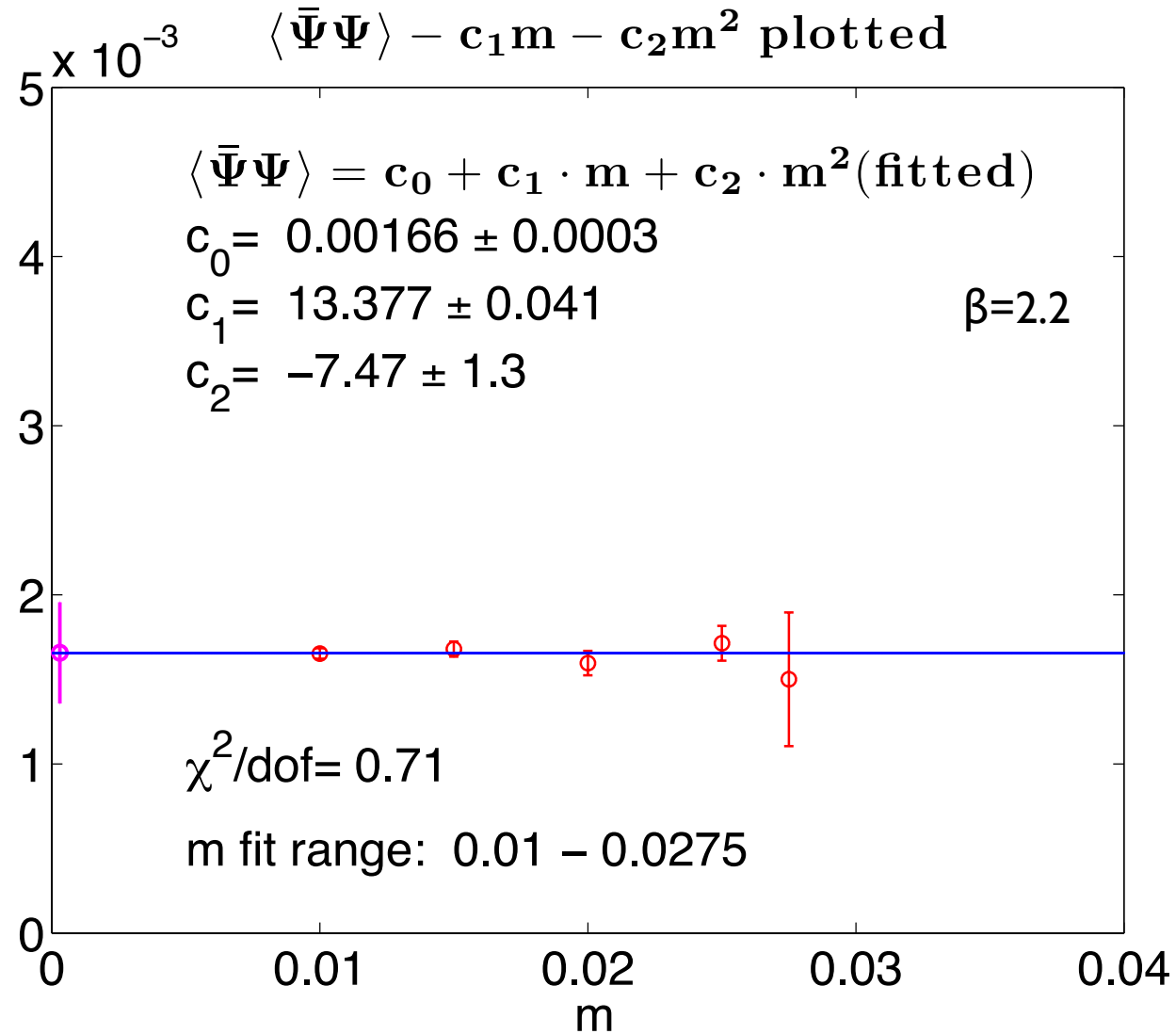


$m \rightarrow 0$  and  $a \rightarrow 0$  limits?    finite volume effects?

useful to compare with other methods:

- SF?
- MCRG?
- two new methods we are developing:  
current correlator moments and wilson flow

# small chiral symmetry breaking condensate



- two independent extrapolation
- condensate very small
- would not be decisive without other tests



conformal scaling test with FSS  
heavy use of RG theory

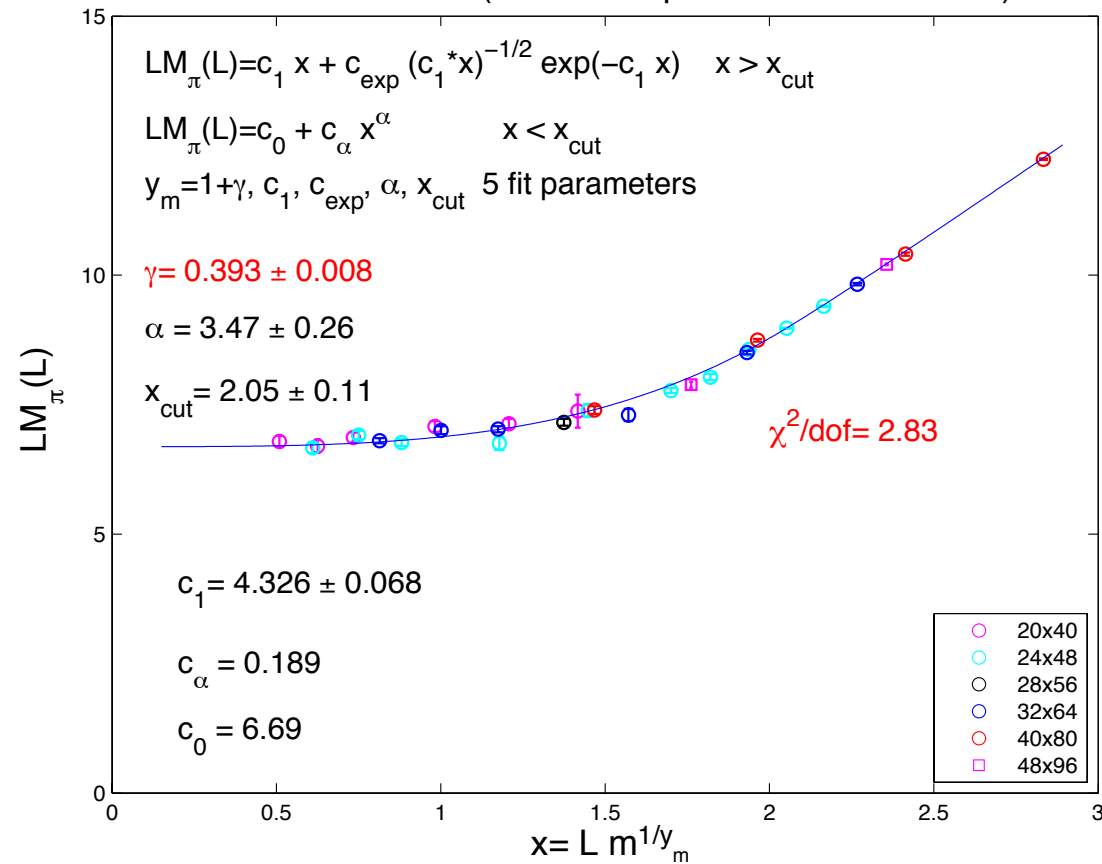
$$LM = f(x) + L^{-\omega} g(x)$$

$$x = m^{1/1+\gamma} L$$

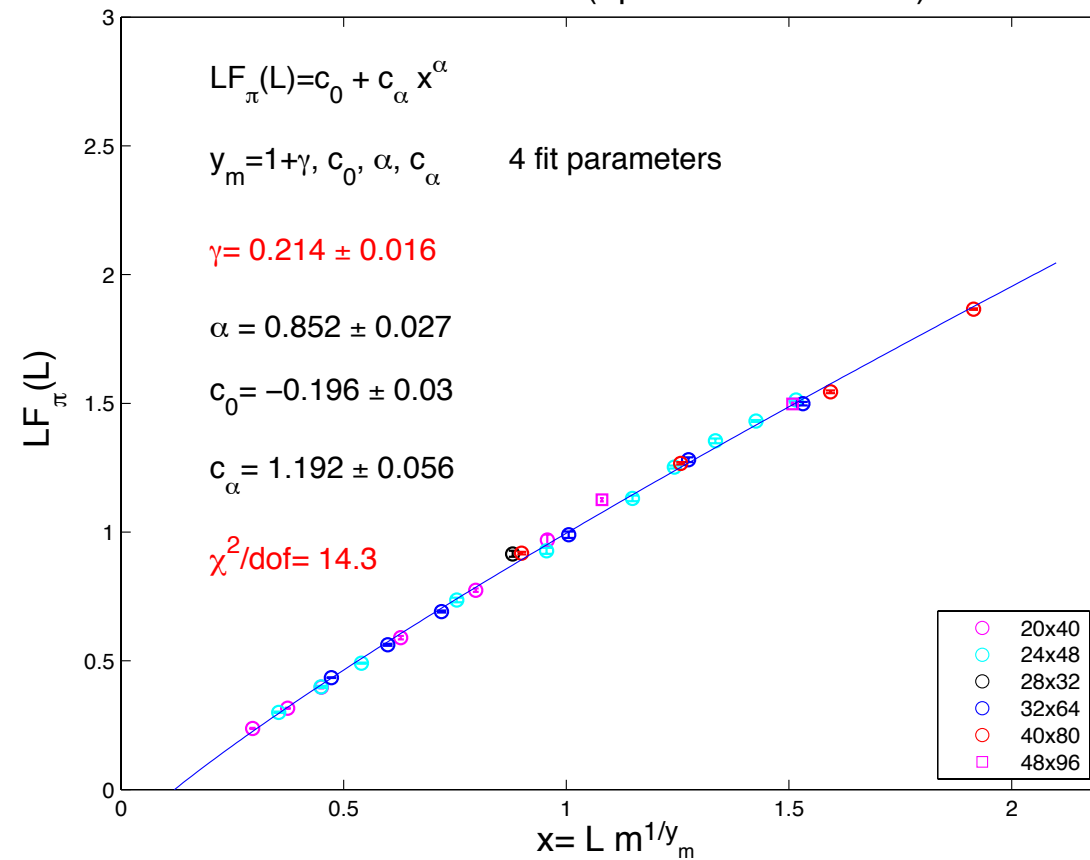
$$\omega = \beta'(g^*)$$

# conformal scaling test with FSS – physical model fit

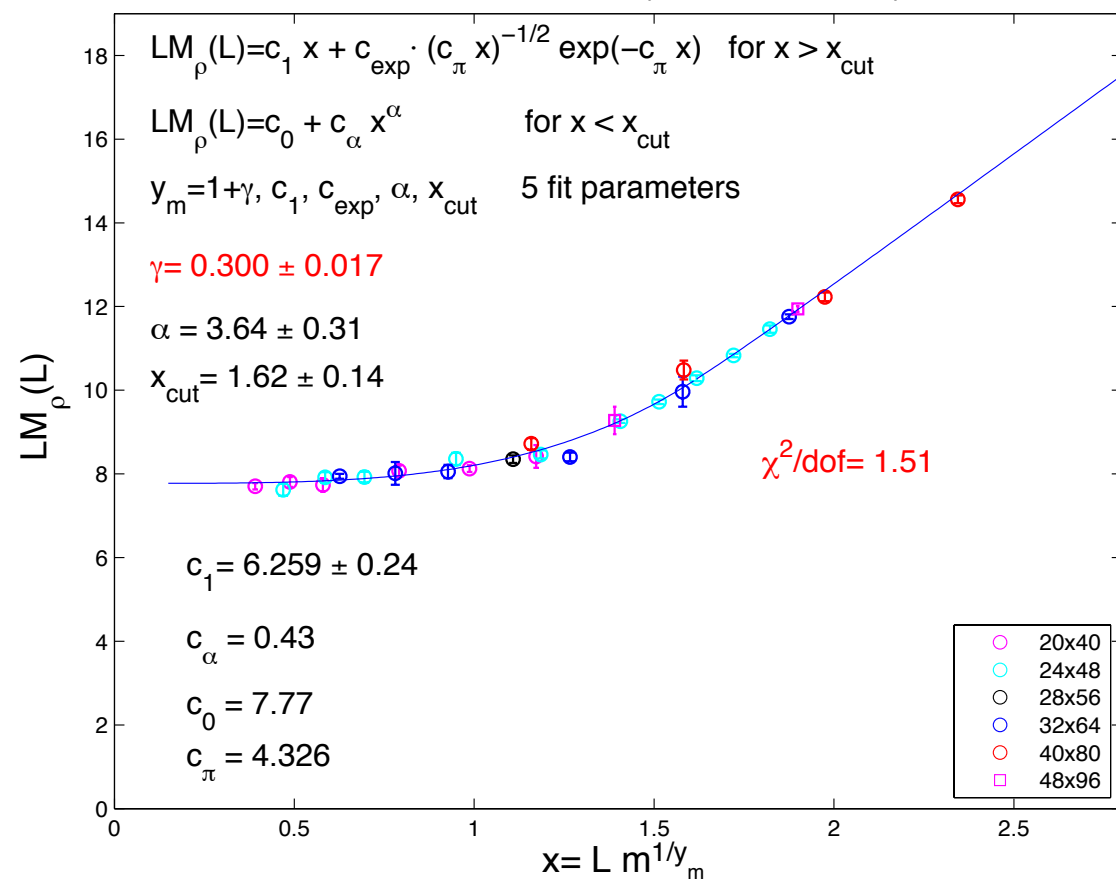
conformal FSS (Goldstone pion – PCAC channel)



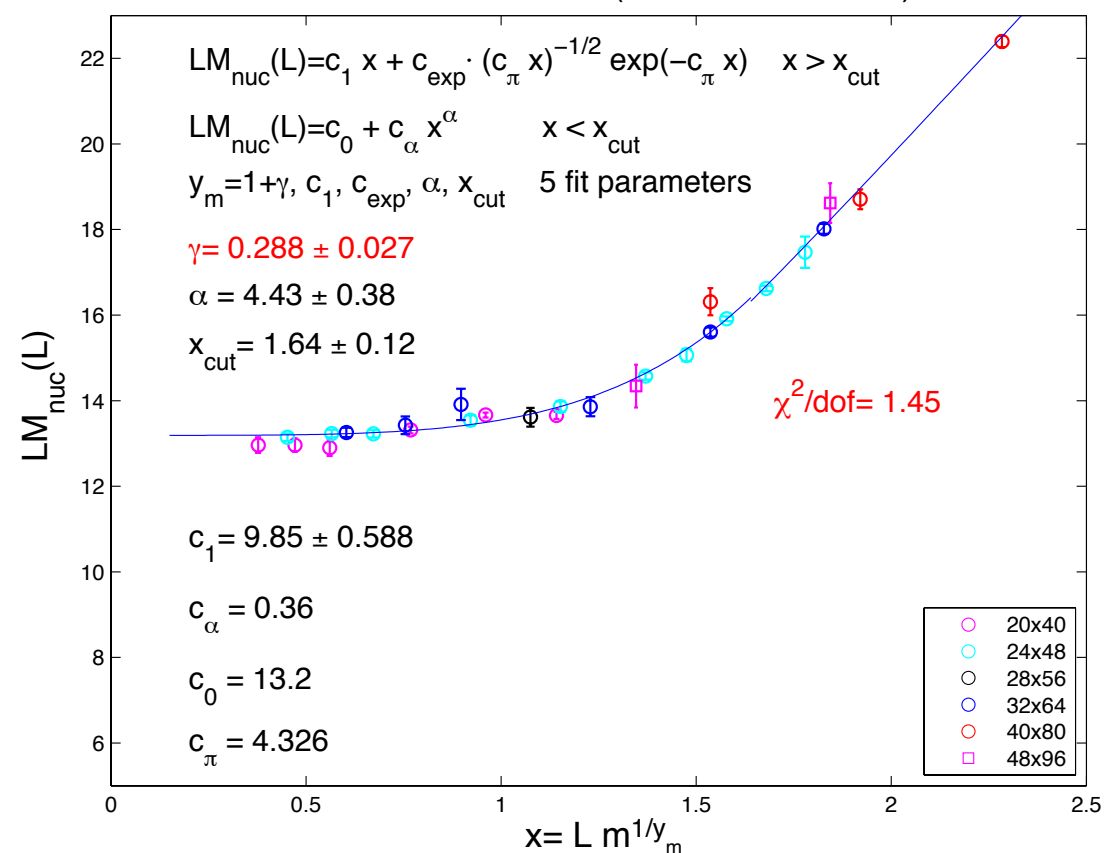
conformal FSS (Fpi – PCAC channel)



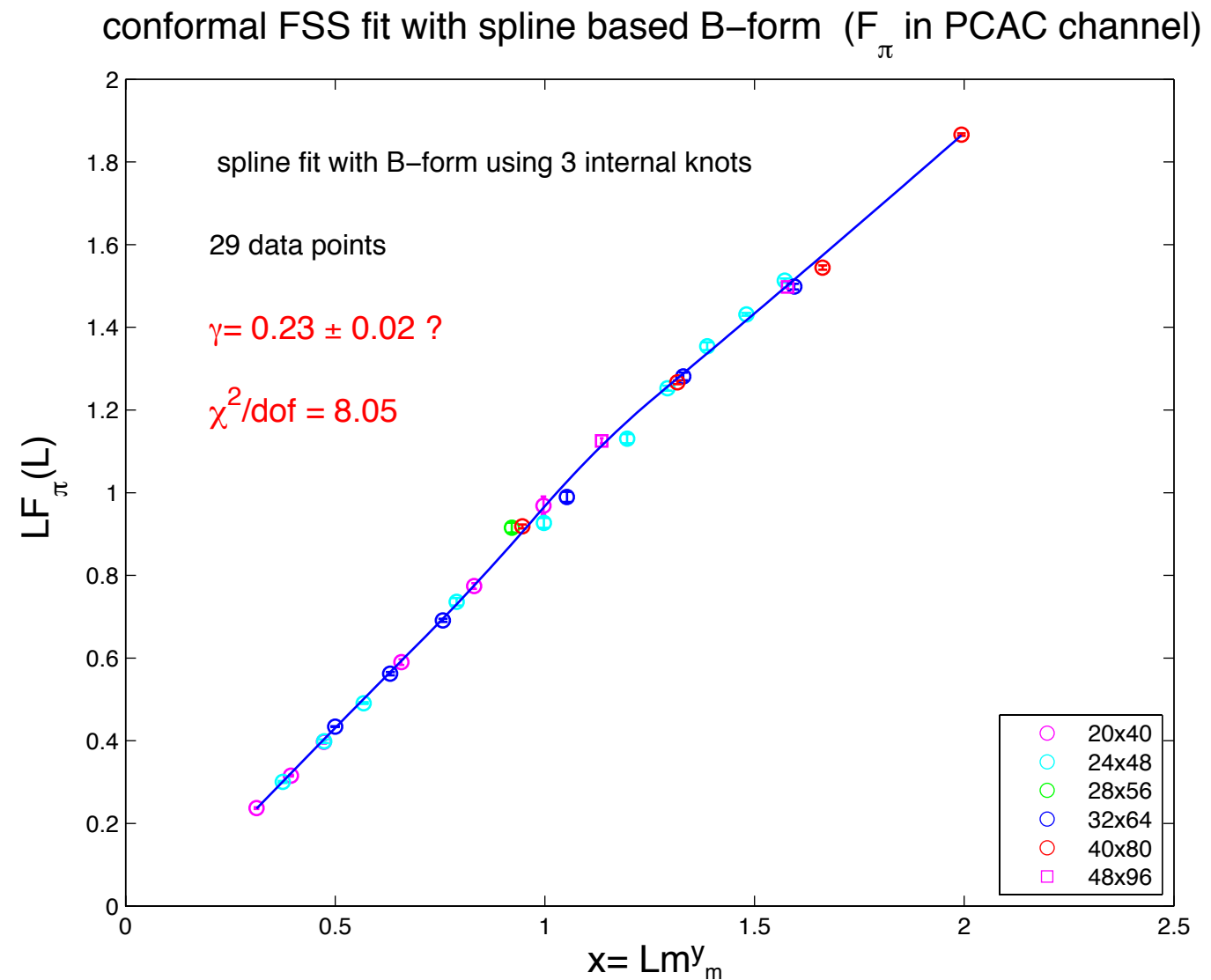
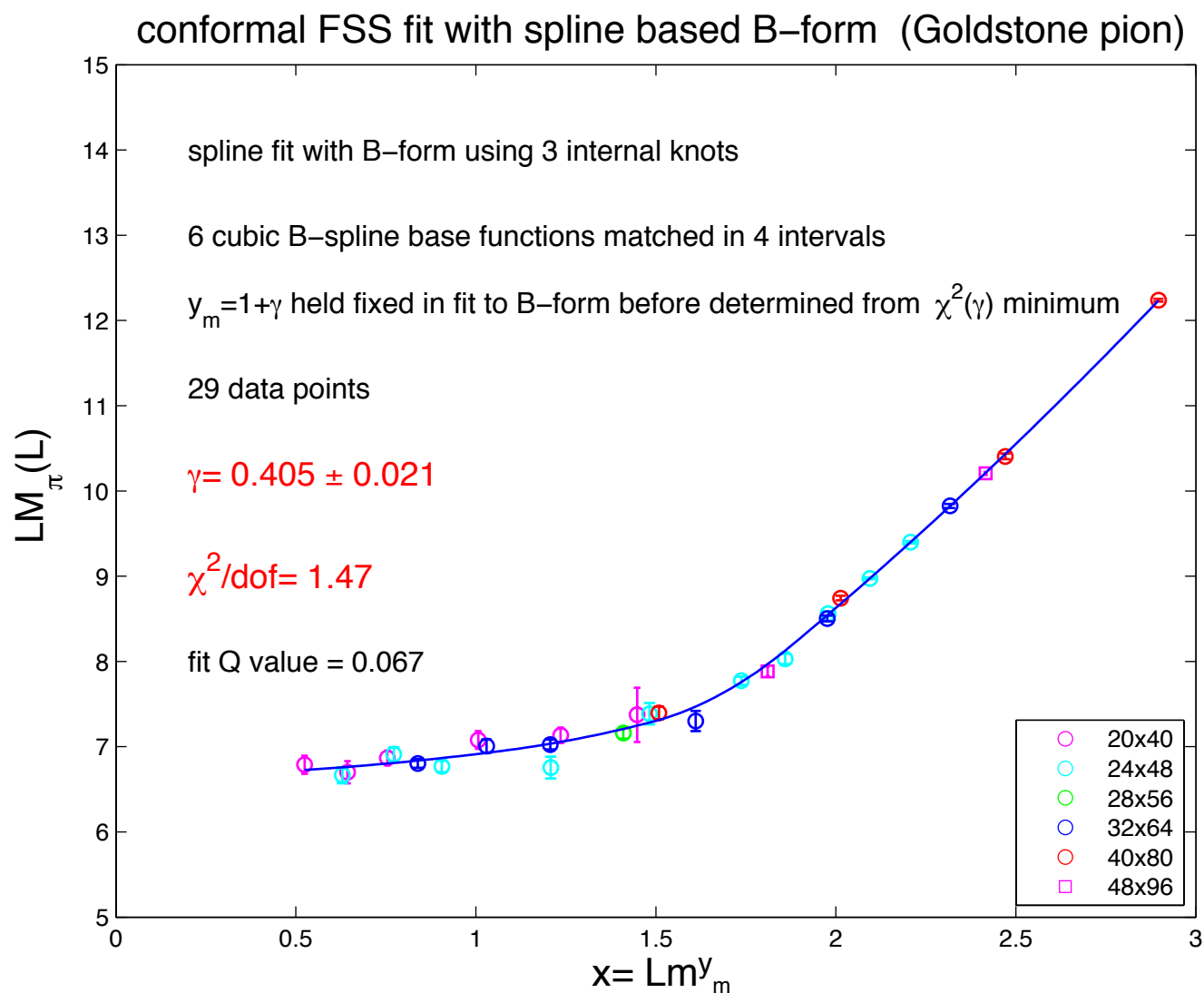
conformal FSS (cRho2 channel)



conformal FSS (cNucleon channel)



# conformal scaling - spline B-form fits



is this glass half full or half empty?

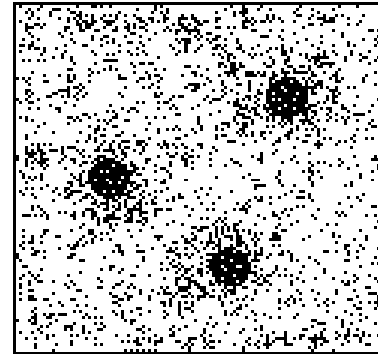
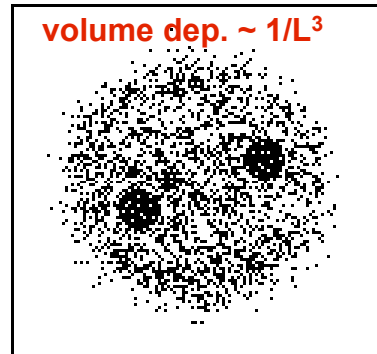
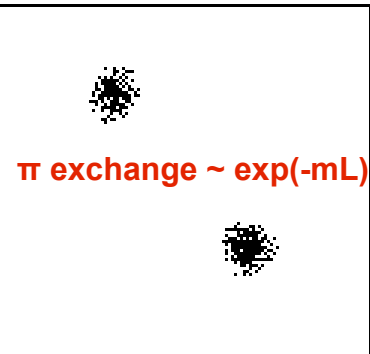
can chiral symmetry breaking fake scaling form?

# Deceptions of $\chi$ SB FSS behavior:

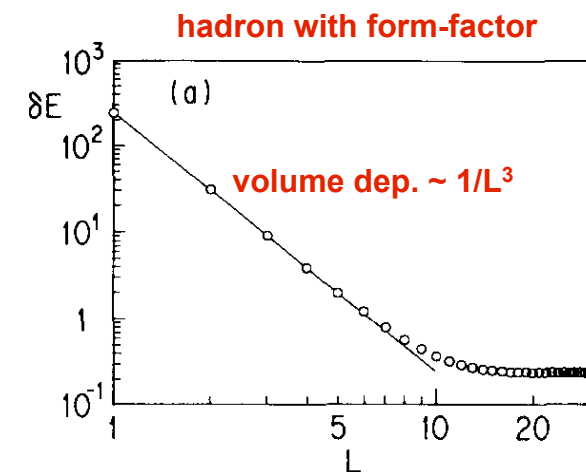
large volume  
hadrons point-like

squeezed wavefunction

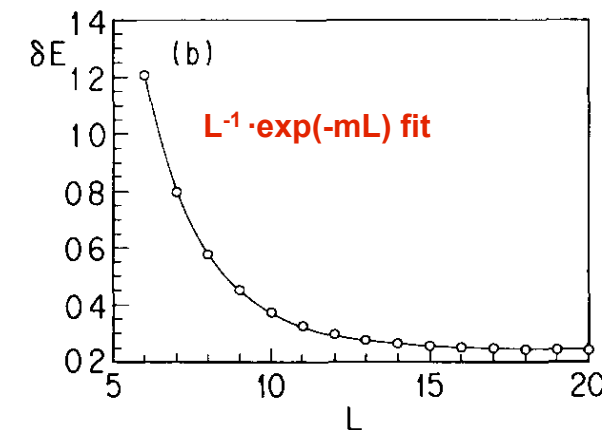
crossover to femto world



$$\hat{V}(\vec{k}) = \frac{F(\vec{k})^2}{\vec{k}^2 + m^2} \quad \text{extended hadron with form factor}$$



$$F(k) = \frac{1}{1 + c \cdot \vec{k}^2}$$



$$F(k) = \frac{1}{1 + c \cdot \vec{k}^2}$$

$$\delta E = \sum_{\vec{n}} V(\vec{n}L) \quad \text{hadron self energy from interaction with images}$$

$$\delta E = \frac{1}{L^3} \sum_{\vec{n}} \hat{V}(\vec{n} \frac{2\pi}{L}) \quad \text{Poisson resummation, } \hat{V}(\vec{k}) \text{ is the Fourier transform}$$

$$\hat{V}(\vec{k}) = \frac{1}{\vec{k}^2 + m^2} \Rightarrow V(r) = \frac{e^{-mr}}{r} \quad \text{for large } r \text{ in point-like approximation}$$

$$\delta E \approx V(0) + 6V(L) \quad \delta E \approx \frac{e^{-mL}}{L} \quad \text{point-like interaction for large } L \text{ (non-relativistic)}$$

Text

Lüscher made it relativistic using field theory

Leutwyler put in the chiral vertices, hence the  $\tilde{g}(mL)$  form in chiral PT

the size where the  $1/L^3$  correction to the masses disappears and the exponential behavior sets in depends on the behavior of the hadron form factor

the characteristic inverse power vs. exponential behavior can frustrate at limited lattice sizes the analysis of chiral vs. conformal hypotheses

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**Nf=12 SU(3) fundamental rep summary:**

- We run in the weak coupling phase
- At fixed coupling and very small fermion mass we see confining potential and finite temp  $\chi^{SB}$  transition
- The effective anomalous dimension  $\gamma$  is not consistent across channels  
can be explained by scaling violation effects or underestimated errors?

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no comment on MCRG

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Running coupling problems in  
TPL and SF schemes:

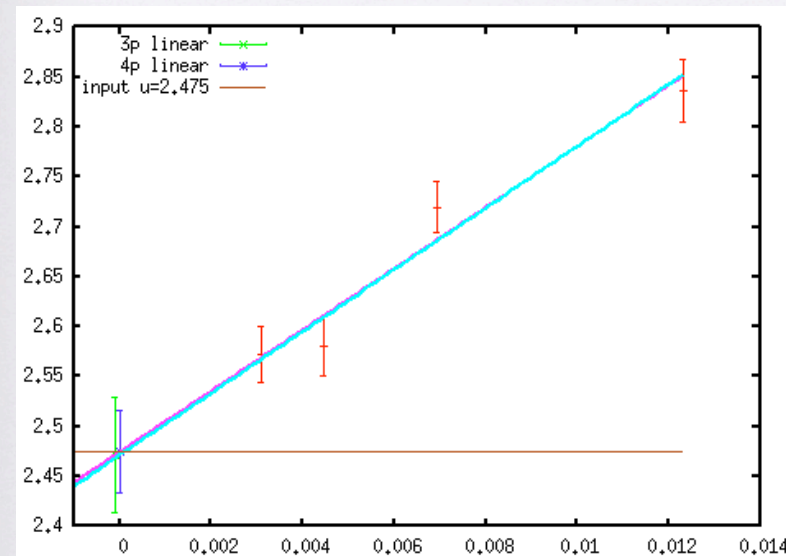


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- The effective anomalous dimension  $\gamma$  is not consistent across channels can be explained by scaling violation effects or underestimated errors?
- Running coupling methods like TPL and SF have problems to control systematics  
no comment on MCRG

Running coupling problems in TPL and SF schemes:

Continuum extrapolation on TPL scheme

$\Sigma(g^2(L), L/a; s)$



**s=1.5 step scaling**  
 $L/a=6 \rightarrow L/a=9$   
 $L/a=8 \rightarrow L/a=12$   
 $L/a=10 \rightarrow L/a=15$   
 $L/a=12 \rightarrow L/a=18$

2 loop prediction  
in this region is  
 $\sigma(u = 2.48) \sim 2.54$

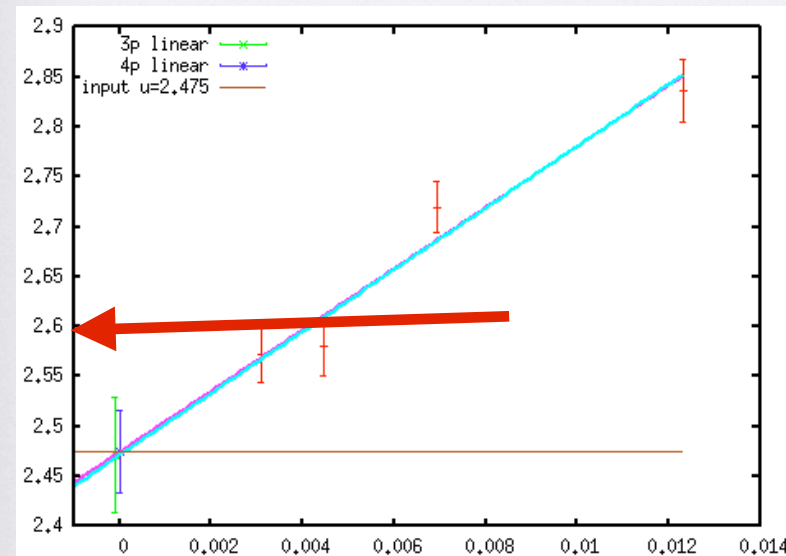
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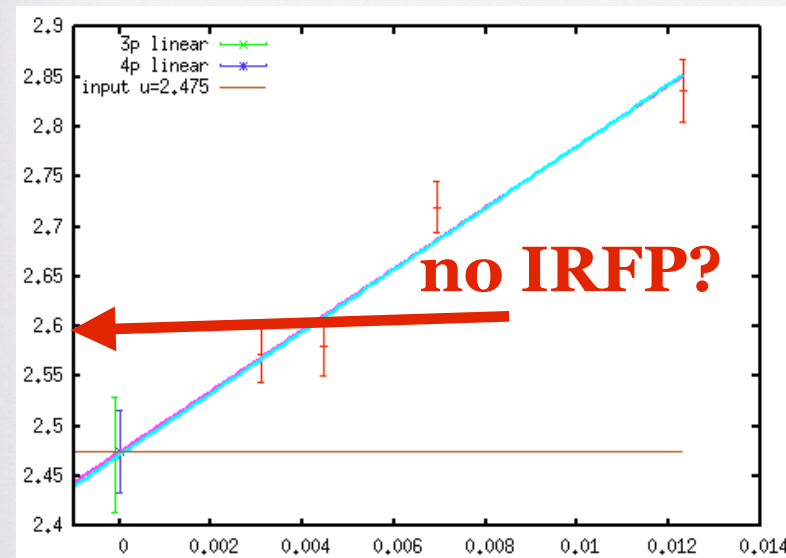
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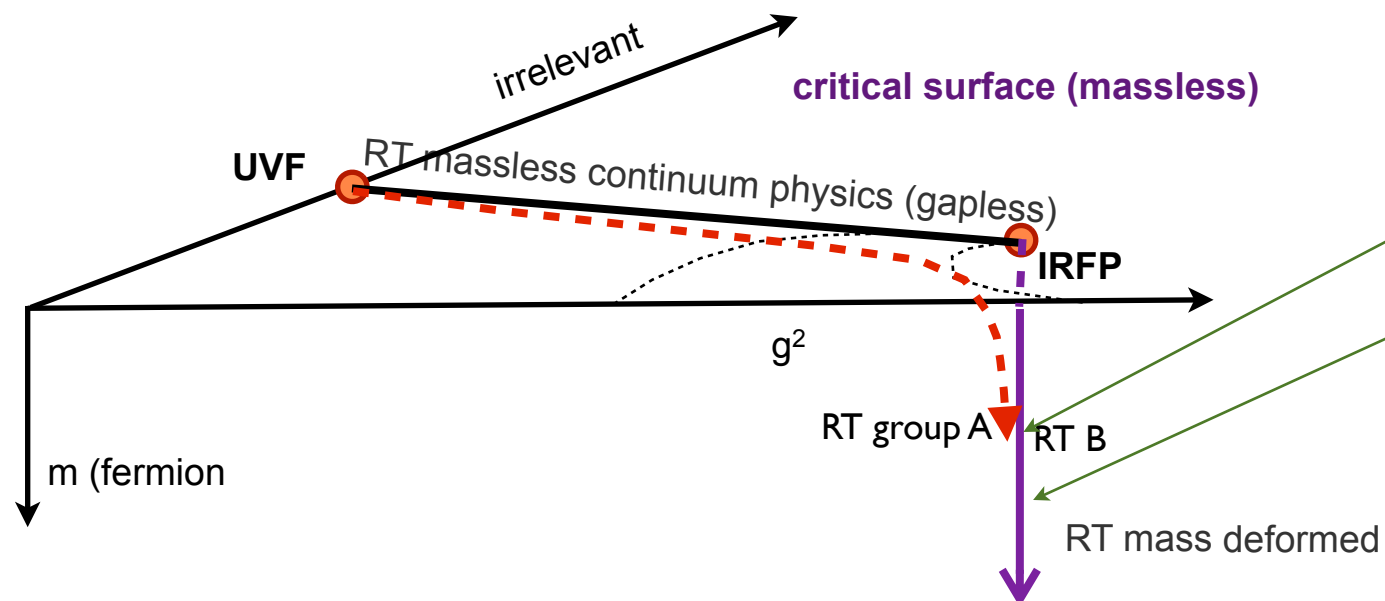
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- We are working on two new running coupling methods with massless fermions using moments of current correlators and wilson flows both are  $g(L)$
- Difficult decision on the  $N_f=12$  model: we would probably prefer to put all the resources into the sextet model without the community controversies at  $N_f=12$
- But sextet project benefitted directly from what we have learned from  $N_f=12$

**backup slides**

# conformal scaling and scaling violations



if model had conformal IRFP

two interchangeable RT descriptions?

continuum mass deformed conformal theory is on RT coming out of IRFP

I worked out as an example all the details of 3D scalar theory (Ising model) with IRFP

textbook material

Del Debbio and collaborators  
early conform apps

free energy on RT:

$$f(u_1, u_2, \dots) = \underbrace{g(u_1, u_2, \dots)}_{\text{analytic}} + \underbrace{b^{-d} f_s(b^{y_1} u_1, b^{y_2} u_2, \dots)}_{\text{singular}}$$

$y_1 > 0$  only relevant exponent in our case

$u_1 = t \sim m$  identified,  $y_1 = y_m$  in Technicolor notation

$y_2$  controls scaling violations, leading correction term

analytic function which can have terms like  $\sim m^k$  are typically sub-leading

Fisher and Brezin worked out most of what we know!

similarly, in conformal finite size scaling analysis:

$$\xi / L = f_1(x) + L^{-\omega} f_2(x) \quad \text{with} \quad x = Lm^{1/y_m}$$

correlation length measured in L units

This directly transcribes to hadron masses and  $F_\pi$

finite size scaling correction terms require  
very accurate data

RG scaling of 2-point function:

$$G^{(2)}(r, m, u_2, \dots) = b^{-2d} G(r/b, b^{y_m} m, b^{y_2} u_2, \dots)$$

from  $G^{(2)}(r, m, u_2, \dots) \sim e^{-Mr}$  asymptotics with  $M \sim m^{1/y_m}$  scaling follows

leading correction to the scaling term should be  $\sim m^\omega$  where  $\omega = \beta'(g^*)$

analysis would change with second relevant operator at IRFP!

- analytic terms exists, but no reason to be leading conformal scaling correction

- correlators of composite operators require inhomogeneous RG!



# Strategy I: $L=\infty$ extrapolation first and then scaling test in $m$

Chiral hypothesis

(in)complete analysis on both sides

Conformal hypothesis

chiral logs not reached yet!

( $N_f=8$ , or  $N_f=12$ )  $N_f=2$  sextet easier reach

$$(M_\pi^2)_{NLO} = (M_\pi^2)_{LO} + (\delta M_\pi^2)_{1-loop} + (\delta M_\pi^2)_{m^2} + (\delta M_\pi^2)_{a^2 m} + (\delta M_\pi^2)_{a^4}$$

$$\sim m^2 \quad \sim a^2 m \quad \sim a^4$$

$$(M_\pi^2)_{LO} = 2B \cdot m + a^2 \Delta_B$$

would require more data

$$(\delta M_\pi^2)_{1-loop} = [(M_\pi^2)_{LO} + a^2]^2 \ln(M_\pi^2)_{LO}$$

$$M_\pi^2 = c_1 m + c_2 m^2 + \text{logs}$$

fitted function for all Goldstones

$$M_{nuc} = c_0 + c_1 m + \text{logs}$$

nucleon states, rho, a1, higgs, ...

$$(F_\pi)_{LO} = F, \quad (\delta F_\pi)_{1-loop} = [(M_\pi^2)_{LO} + a^2] \ln(M_\pi^2)_{LO}$$

chiral log regime was not reached in fermion mass range

$$(\delta F_\pi)_{m^2} \sim m, \quad (\delta F_\pi)_{a^2 m} = a^2$$

kept cutoff term in F

$$F_\pi = F + c_1 m + \text{logs}$$

fitted function

$$\langle \bar{\psi} \psi \rangle = \langle \bar{\psi} \psi \rangle_0 + c_1 m + c_2 m^2 + \text{logs}$$

chiral condensate

$$M_\pi = c_\pi \cdot m^{1/y_m}, \quad y_m = 1 + \gamma$$

leading conformal scaling

functional form for all hadron masses

$$F_\pi = c_F \cdot m^{1/y_m}, \quad y_m = 1 + \gamma$$

same critical exponent

$$\langle \bar{\psi} \psi \rangle = c_\gamma \cdot m^{(3-\gamma)/y_m} + c_1 m$$

Del Debbio and Zwicky

Asymptotic infinite volume limit has not been reached yet in important candidate models for conformal window

infinite volume conformal scaling violation analysis ?

conformal finite size scaling analysis and its scaling violations ?

